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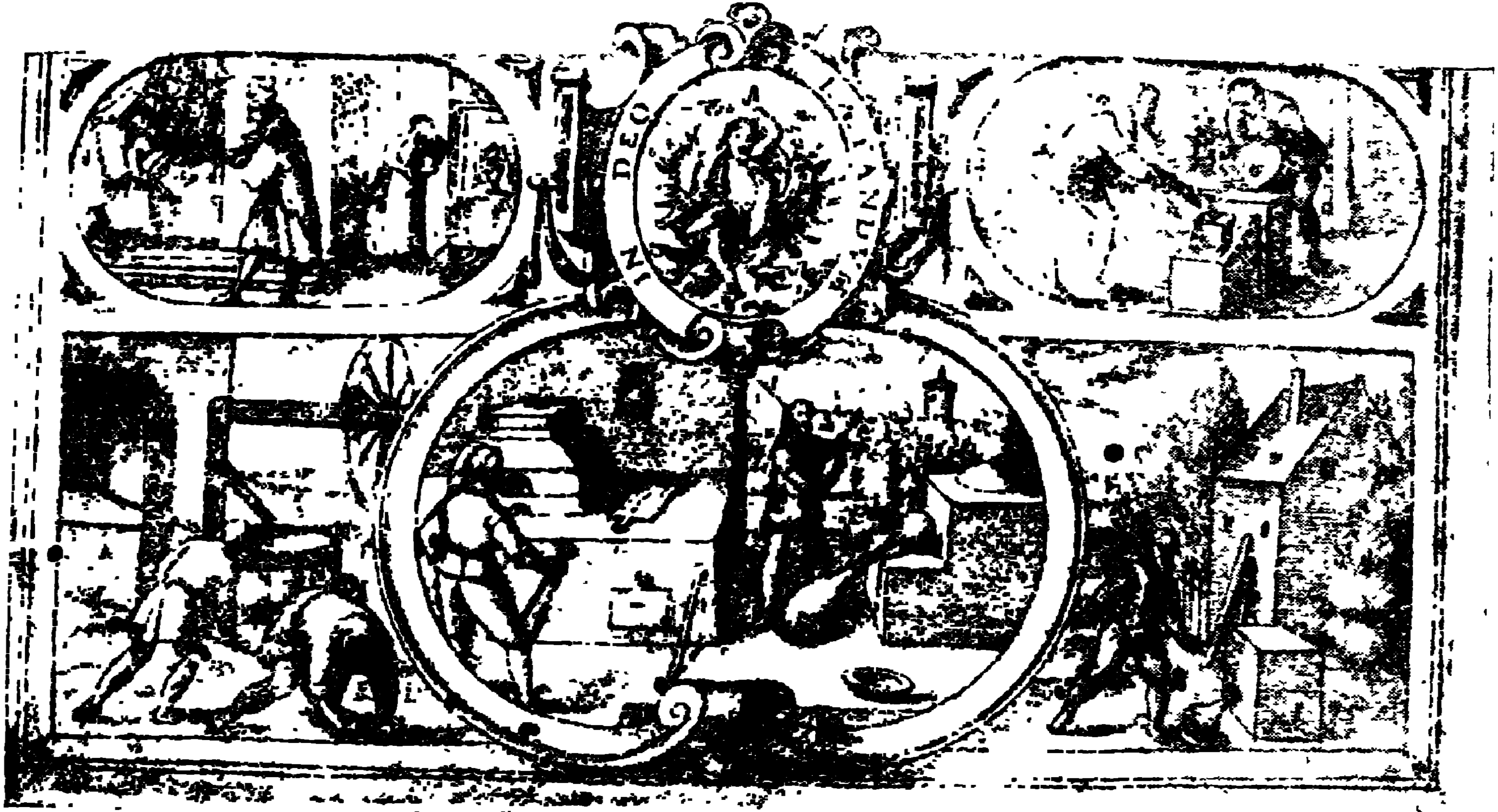
THE STORY OF
THE CHEMICAL ELEMENTS



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THE STORY OF
THE CHEMICAL ELEMENTS

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LONDON: GEORGE NEWNES, LTD.
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PREFACE.

I HAVE made an attempt to put forth in some kind of orderly sequence a few of the chief guiding conceptions of chemistry; endeavouring, on the one hand, to avoid technical details, and, on the other hand, to illustrate these conceptions by describing many common facts. I have tried to keep the attention of the reader fixed on the great generalisations of chemistry; and I have done my best to shew that these generalisations find constant application in the occurrences of everyday life.

M. M. PATTISON MUIR.

CAMBRIDGE, *October* 1896.

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THE STORY OF
THE CHEMICAL ELEMENTS.

CHAPTER I.

INTRODUCTION.

ANYONE who observes with some care the material occurrences which are constantly taking place around him must notice, that although these events differ much from one another, very many of them have this in common that in them there is change of substance, or change of form, or change of properties. As a fire burns there is a change of coal, or wood, to smoke, flame, and ashes; although we see no new thing produced when coal gas is burning, yet our sense of smell helps our sense of sight, for we know that if the gas were not changed into some other thing when it is burnt we should smell the unchanged gas; when an oil lamp is burning badly some of the substances that are formed from the oil make known their presence by unbearable odours. From the dry and winter-stricken trees the return of spring calls forth green buds, and summer changes these to leaves, and autumn dyes those leaves in crimson, purple, and gold; the blossoms on the fruit-trees that herald the

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near approach of a milder season change after a time into fruits, and on the surface of these fruits the colour deepens as under the influence of the sun new substances are produced within them; the fields are ploughed and the seed is sown, and from these seeds corn and other kinds of grain spring up in due time, and then the pale green ears acquire a warmer hue till the waving of the golden grain tells that the time has come for this cycle of changes to be completed. Water changes to ice, and rain to hail and snow; the mountain side that to-day is dry and silent to-morrow is vocal with the sound of dashing brooks; and the mountains themselves crumble slowly and their rocks are changed to the dust of the plains.

And if we turn to man's dealings with material nature outside himself we shall find that it is hardly an exaggeration to say that the whole of these dealings consist in taking advantage of changes of substance, properties, or form that occur in material things without his intervention, or in accomplishing novel changes by creating conditions different from those that prevail where he does not interfere.

The timber which is used in making houses, furniture, ships, and many other things that enter into our daily lives, is one product of those complicated changes that are brought about by the growing tree in the food it obtains from the air by its leaves and from the soil by its roots. There are plants which change the substances they absorb by their roots and leaves into sugar, and when these plants are crushed and the liquid part of the sweet juice which exudes is boiled away sugar remains. In the living laboratories of other plants are produced, from materials the same as, or very like, those that the sugar-cane changes into sugar, dye stuffs such as madder and indigo, or sweet-smelling resins such as frankincense and myrrh, or essential oils as cedarwood oil, oil of bergamot, and attar of roses, or gums as gum tragacanth and gum arabic, or such things as guttapercha and indiarubber, or substances such as quinine, morphine, and salicylic acid that afford some relief to those who suffer pain.

Most of the substances that are used as human food are the products of changes that occur in those living organisms, plants and animals. The plants absorb comparatively simple substances from the air and the soil, and from these they build up more complex things such as starch and sugar; plants are eaten by animals which carry further the building up processes that the plants began; and both vegetable and animal substances are consumed by man and are changed into the highly complex materials that form the organism which is for ever synthesising itself from simpler kinds of matter, and is constantly being resolved into less complex forms of substance.

The manufacturing industries are so many examples of the intelligent direction to definite ends of changes in material things. Iron ore is brought in the blast furnace under such conditions that the red earthy stone is converted into lumps of cast iron; and when this iron is melted and air is blown into the fluid mass it undergoes another transmutation into hard, lustrous, malleable steel. Sulphur, or it may be pyrites, is burnt in a stream of air, and the suffocating gas so produced is conducted into large leaden chambers where it mixes with steam and with another reddish coloured gas from which it removes oxygen; the product of these changes is oil of vitriol, an acrid, corrosive, liquid that is used in almost every manufacturing process.

Common salt is heated with oil of vitriol, and a mixture of the product with coal and chalk is melted in a furnace; the black solid formed by this operation is lixiviated with water, and when the liquid is evaporated carbonate of soda is obtained. Carbonate of soda is transformed into caustic soda by boiling with milk of lime; and when caustic soda is heated with fat, olive oil, or cottonseed oil, the products are glycerin and soap. Scrap iron is heated with pearl ash and hoofs, horns, or fragments of hides, or leather; the product is treated with water, and large, yellow, transparent crystals of yellow prussiate of potash are obtained by filtering this liquid and evaporating it. The yellow prussiate is dissolved in water and a solution of iron in an acid is added to this liquid; the result is the deep blue pigment called Prussian blue. Sand, or finely ground quartz, is mixed with carbonate of soda, or pearlash, and the mixture is melted in pots placed in a very hot furnace; when the melted mass is poured on to a flat metal table a sheet of transparent, colourless, glass is formed.

Coal tar is distilled; a portion of the colourless liquid which distils over is mixed with *aqua fortis*, and the heavy reddish oil, smelling like oil of almonds, which is produced by this treatment is warmed for some time with iron filings and concentrated vinegar, and is then distilled. The colourless liquid that distils over is called aniline; and from that liquid is produced, by suitable treatment, a vast number of coloured substances wherewith cotton, woollen, and other goods may be dyed every shade and variety of colour, both beautiful and crude.

The juice of grapes acquires new properties after being exposed to the air for a time; the liquid loses some of its sugar, and in place thereof a volatile liquid, endowed with strange powers and potencies, is produced: the juice of the fruit has changed into "wine that maketh glad the heart of man." When barley that has begun to germinate is heated to a proper temperature, and is then mashed with water, and the liquid so produced is mixed with yeast and kept slightly warm, a change occurs similar to that which happens in grape juice exposed to the air; sugar disappears, and alcohol and carbonic acid gas are formed: the decoction of malted barley has been transmuted into beer.

And what is the art of cooking but the intelligent direction of certain possible transmutations in the substance and properties of food-stuffs so as to produce new materials that nourish the body, please the palate, and enliven the wits of man?

The story of chemistry is the story of the unravelling of such changes and transmutations of material things as those that have been referred to in the preceding paragraphs.

It was supposed in former days that anything might be changed into anything else, provided the proper conditions could be arranged. On this supposition was based the tedious art of alchemy; for it was not on a vague guess, but on what they took to be a universal law, to wit, the infinite mutability of material things, that the long-suffering, much-enduring, alchemists rested their strange processes. Noticing the profound and unexpected transmutations that occur so frequently in things, the alchemists gave an affirmative answer to the question which these transmutations kept dinning in their ears; —Can any material thing be changed into any other thing? And then driven to seek for some stable, unchanging. reality, by the innate longing of humanity for rest, the alchemists hit upon the enticing hypothesis of The One Thing, which they called also the Essence, the Stone of Wisdom, the Blessed Water, the Philosopher's Stone, and many other names.

Those early readers of the story of the changes of material nature found that a language had to be constructed wherein they might express their reading of the legend; and the fundamental conception of their rendering found expression in such sentences as these:—"There abides in nature a certain form of matter which, being discovered and brought by art to perfection, converts to itself, proportionally, all imperfect bodies that it touches."

" . . . For 'twere absurd
To think that nature in the earth bred gold

> Perfect in the instant; something went before.
> There must be remote matter.
>
> . . . .
>
> Nor can this remote matter suddenly
> Progress so from extreme unto extreme
> As to grow gold, and leap o'er all the means.
> Nature doth first beget the imperfect, then
> Proceeds she to the perfect."

And, basing their work on this conception of a perfect matter which was able to convert to itself all imperfect bodies, the alchemists recognised that much labour was required to gain that perfect matter; they recognised, as one of themselves stated, that "Nature moves not by the theorie of men, but by their practice, and surely wit and reason can perform no miracles unlesse the hands supplie them." In setting their hands to supply the material conditions favourable to the movement of nature, they were convinced that nature moved in the direction they thought she ought to move in and by ways which they were able to mark out for her progress.

Many centuries passed before the investigators of nature shewed some willingness to accept their true position as parts of the nature they sought to comprehend. Most of the earlier seekers after a knowledge of nature began by building walls each of which marked off one portion of natural occurrences from the rest. I do not suppose they built these walls consciously, rather they thought they saw walls where no barriers were. The alchemists were very busy within their intellectual sheep-pens, as the chemists of to-day are most active in the larger walled gardens of their intellectual domain; but the alchemists made fewer breaches in their encircling barriers than we make now in ours. And I think we recognise, what our predecessors could not acknowledge, that the territorial divisions which must be established are of our own making, and are made only for the purpose of helping us to understand the infinitely complex whole.

The history of science may be described as the history of the breaking down, and the crumbling away, of artificially constructed barriers. All the great men of science have been famous wall-breakers. The instruments of demolition which these men wielded have been derided by the ignorant wise men who declared the walls would never fall; the noise of the crashing barriers has travelled slowly to the ears of those who did not wish to hear, and in the vacant places solid constructions have continued to be evident to the eyes which did not desire to see.

It is worthy of remark that the central conception of the alchemists, which, nevertheless, led to their pigeon-holed representation of nature, was the unity of natural phenomena. If their arguments were translated into the language of to-day they would be somewhat as follows—Plants grow from seeds, and the plant is a very different thing from the seed; animals become larger, stronger, and more complete as they grow older; the plant may well be called more perfect than the seed, and the full grown animal more perfect than the immature animal; both plants and animals grow, come to their prime, and decay; and there are degrees of perfection in the animal and vegetable worlds. Now—we may suppose the argument of the alchemist to continue—nature works in simple ways; man is the crown and glory of creation, and it is foolish to suppose that man cannot understand nature; to preserve the unity of nature it is necessary that minerals and metals and all inanimate things should grow, and change, from less perfect to more perfect forms; as there are degrees of perfectness and dignity among living things, so must there be degrees of perfectness and dignity among all things; some metals disappear in acrid liquids, and these metals are generally easily worn away, they are readily melted and burnt to dross; but some other metals are not swallowed up by corrosive liquids, nor are they worn away with ease, nor readily changed in the fire; there are evidently noble and base metals, perfect and imperfect metals; and as the less perfect seed under proper conditions produces the more perfect plant, and the plant is rendered yet more perfect by cultivation, so the imperfect metals change slowly into those which are more perfect, and this slow process of change can be hastened by man's art and device.

The argument from analogy was pushed by the alchemists further than this. What they said may be rendered somewhat in this way:—It is evident that living things are more perfect than inanimate things; if therefore there are changes from less perfect to more perfect forms among living things, much more must changes from immature to mature forms be constantly proceeding among dead things like minerals and metals; and as these minerals and metals are less perfect than plants and animals, it is probable that the plasticity of the minerals and the metals will be greater than the plasticity of living animals and living plants; hence there will not be those marked lines of demarcation in the mineral world which we find in the animal and vegetable worlds; it will be a comparatively easy thing to grow a noble metal like gold from ignoble metals like lead or copper, although it is an impossible thing to change one kind of animal into another or one sort of plant into another sort of plant.

A vague conception of the unity of nature of this kind led to little accurate knowledge; the conception could not be applied strictly and in detail to natural occurrences; all that could be done was to perform a vast number of inaccurate and incomplete experiments, and to state the results in the loose and slipshod language of the vague but sonorous hypothesis which prompted the experiments. And so although the hypothesis postulated the unity of nature there was no unity in the experimental results which were collected to support the hypothesis. The resemblances and the dissimilarities between natural occurrences are not to be discovered by reasoning about an order of nature which exists only in the brain of the reasoner. A man who sets out to discover what is must endeavour to put aside all his notions of what ought to be; it is only when he has gained a solid foundation of verified and accurately stated facts that he may venture to make a definite guess concerning the cause of the facts he has collected, but unless he makes clearly stated guesses—that is, scientific hypotheses—he will remain a mere collector of half facts and will never become a scientific investigator.

We shall endeavour in the following chapters to trace the methods which chemists have used to elucidate a certain class of changes that material things undergo, and to state and illustrate some of the more important general results they have attained by the application of these methods.

CHAPTER II.

THE CHARACTER OF CHEMICAL CHANGE.

As the changes which material things undergo were examined with some care, a distinction came to be made between those changes wherein the properties and also the composition of the matter affected are modified, and those wherein the composition of the matter is not altered, although its properties are changed.

A few simple experiments will illustrate the more prominent differences between these two kinds of changes.

If a piece of thin, clean, iron wire is held in the hot, non-luminous flame of a Bunsen burner,* the iron glows and emits light. If the wire is removed from the flame after a few seconds, an examination of the wire will show that the iron has not been changed into anything else so far as can be judged by the senses of sight and touch.

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* The Bunsen burner is an ordinary gas jet over which fits a cylindrical metal tube pierced near the lower end with two large holes; the mixture of air and gas is lighted at

When a few chips of wood are placed in a dry test tube which is then gradually heated by a Bunsen burner, the wood soon darkens in colour, and after some minutes moisture is seen forming on the upper parts of the tube, and something is given off with a very decided odour. If the heating is continued for a few minutes, and a lighted taper is then brought to the mouth of the tube, the vapours that are coming off take fire. The senses of sight and smell assure us that the wood has been changed by heating it, into things which are quite different from wood; and this conclusion is verified by the test of the lighted taper.

If a few small pieces of sugar are heated in a dry test tube, in the same way as the chips of wood were heated in the last experiment, the sugar chars and gives off badly-smelling vapours, which ignite when a lighted taper is brought to the mouth of the tube after the heating has been continued for some minutes. The sugar is evidently destroyed, and things which are not sugar are formed in its stead.

When a few grains of dry salammoniac are

the top of this tube. A considerable volume of air enters through the holes in the metal tube, and when the mixture of gas and air which issues from the top of the tube is ignited, the whole of the gas is completely burnt and a flame is obtained which is very hot, and is not luminous as it is free from particles of unburnt carbon.

placed in a dry test tube, and the lower end of the tube is heated very gently in the flame of a Bunsen burner, the salammoniac gradually disappears from the heated part of the tube, and a white solid slowly forms on the upper, cool part of the tube. So far as appearance goes, this white solid is the same as the salammoniac that was heated; if minute portions of the salammoniac and the white deposit are tasted they seem to be identical; and if a little of each is shaken with water both dissolve easily in the water; moreover, if both are boiled with a little soda lye, the smell of ammonia (spirits of hartshorn) is very perceptible in each case. The senses of sight and taste tell us that the salammoniac was not changed into any new substance by heating it, although it was transformed from a solid to a vapour, which again became a solid when it was cooled; and this conclusion is strengthened by the results of the tests with water and soda lye.

So far as they go, these rough experiments indicate that the iron remained iron when it was taken out of the flame, and that the salammoniac was not changed into any new thing by heating until it became a vapour, and then cooling this vapour: at the same time the iron certainly acquired a new property as long as it was kept in the hot gas-flame, for under these conditions it emitted light; and the salammoniac passed from the solid to the gaseous state when it was heated. A change of properties was effected in each case, but this change was not permanent, nor did it seem to be accompanied

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by any change of composition. On the other hand, the senses of sight and smell assured us that both wood and sugar were changed into new things with new properties by the action of heat: in these cases change of properties was undoubtedly accompanied by change of composition; and both changes were permanent, for the things produced by heating wood did not change back into wood, nor were the things formed by heating sugar re-transformed into sugar, when the vessels in which the heatings were conducted were removed from the source of heat.

The iron seemed to remain iron, and the salammoniac seemed to be still salammoniac. But "things are not what they seem;" we must have more conclusive proof.

The alchemists used to say that during the burning of chalk to lime, an *igneous principle*, or a *fiery essence*, passed into the chalk from the fire, and that the caustic properties of burnt lime were due to the presence in it of this igneous principle. Why should not we also assert that the things formed by heating wood or sugar are produced by the addition to the wood or sugar of a calorific principle from the heat, which principle remains permanently in the burnt wood or sugar? Why should not we maintain that a fiery essence passes into iron that is placed in a hot flame, but escapes when the iron is removed from the flame.

The balance has forced the chemist to throw aside the alchemical explanation, and it has enabled him to find an explanation more consistent with the facts by revealing facts which were unknown to the alchemist. If any kind of matter is added to chalk during the conversion of chalk into lime in a kiln, the lime must weigh more than the chalk. But when the lime formed by burning a weighed quantity of chalk is weighed it is found that instead of weighing more, the lime weighs less, than the chalk from which it has been obtained. If one pound of chalk, for instance, is burnt to lime, rather more than half a pound of lime is produced. Some material substance—it may be more than one substance—has been taken away from the chalk in the kiln; and lime is chalk deprived of one, or more than one, of its constituents. Or, perhaps, the burning effected the removal of something from the chalk and at the same time caused the addition of something else, the net result of these two occurrences being a loss of weight.

The result of a few experiments on the change that takes place in the lime-kiln, arranged so that determinations are made of the relative quantities of matter concerned in this change, is to present us with a definite subject for further inquiry. Putting aside speculations about igneous principles and the like—reserving all speculations until we have a fixed basis of accurately ascertained quantitative facts whereon to rest our theories—we must seek to solve the questions which are directly suggested by the result of our first application of the instrument of research which the balance-maker has put into our hands.

What did the chalk lose when it was heated? We did not see anything leaving the chalk. Well, then we must aid our sense of sight; we must try to arrange an experiment in such a way that if anything escapes that something may be caught, weighed, and examined. And we must also make the conditions of our experiment such that if anything combines with the chalk, during the heating of it, we shall be able to detect the removal of this something from the materials that are in contact with the chalk during the experiment. But to conduct such experiments as these means that we acquaint ourselves with the composition of chalk, and the composition of the air in contact with which the chalk is heated, and that we know also the composition of the vessel wherein the chalk is exposed to the action of heat. A large inquiry is at once opened; and that inquiry must be prosecuted by accurate, that is by quantitative, experiments. We shall have to determine whether chalk has a definite composition, or whether its composition is not always the same, we must resolve chalk and lime into their components, and re build these substances from those components, and we cannot do this without giving a very definite meaning to the words *composition* and *components.*

And as with the chalk so with the wood, the sugar, the salammoniac, and the iron. If the iron was not changed into a new thing when it was heated until it glowed, the weight of the iron before the experiment was made must be the same as the weight of the material when the experiment was finished; and that we may positively assert that no change of composition accompanied the temporary change of properties from dull iron to a glowing, light-emitting substance, we must know definitely the composition of the iron before it was heated and after it was heated, and we must determine whether the composition of the air that surrounded the glowing iron did or did not undergo any change. Similar experiments must be made with salammoniac; the composition of the substance must be determined, and the composition of the white *sublimate*[x] which seemed to be unchanged salammoniac must be compared with that of the salammoniac before heating; moreover the loss of weight suffered by the salammoniac must be determined and the weight of the white sublimate must be found, for if no change of composition accompanied the change from the solid to the gas and back to the solid these two weights must be the same. Methods must also be devised and experiments conducted whereby we shall be able to determine the exact compositions of wood and sugar, and the compositions of the things that are produced when wood and sugar are heated; and the experiments must take into account the possibility of the removal of material things from, or the gain of such things by, the surrounding air and the vessels wherein the experiments are conducted.

It was only as chemists, and naturalists in general, recognised that quantities of matter could be measured by their weights, that they began to find a trustworthy method of examining and disentangling the transformations that matter undergoes. However strange, unexpected, and profound a change in the properties of some material substance may be, the balance enables us to find out whether the change has or has not been accompanied by the addition to, or the removal from, the changing substance of some other kind of matter.

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[x] A solid obtained by cooling the vapour formed by heating a solid is called a *sublimate*.

Imagine a box with many different things in it: let there be balls of wood of different colours; lumps of iron, lead, copper, silver, and other metals; pieces of suet; parcels of tea, spices, sugar, coffee and such things, let some of the things in the box be large, and let other things be extremely small. Let it be arranged that nothing is to be taken from the box, nor is anything to be brought into the box, from outside. Let there be two people. One of these examines an object in the box, say a parcel of tea; he then turns his back, while the other person either takes out some of the contents of the parcel of tea, or mixes other things with the tea in the parcel, or does both of these, or does not alter the contents of the parcel but dashes a coat of paint over the outside of it; the first person has then to determine which of the four processes has taken place. It is evident that a couple of weighings would help towards the solution of the problem but would not suffice to solve it. If the parcel weighs the same after the process as before the process, either nothing has been taken out, or if anything has been removed an equal weight of something else (or of some other things) has been put into the parcel. If the parcel weighs less at the end, than it did at the beginning, of the experiment, something has been taken out of it; but something may also have been put in, provided the weight of what has been put in is less than the weight of what has been taken out. A complete solution of the problem would be possible only when the properties of each distinct substance in the box were known, and the quantity of each was known: in other words, to solve the problem it would be necessary to examine the various substances carefully, and to determine the quantity of each in the box, by weighing it, both at the beginning and at the close of the process; if the same weight of each substance was found in the box, outside the parcel, at the end as was found at the beginning of the proceedings, evidently nothing had been taken out of the parcel of tea nor had anything been put into it.

One of the people in our imaginary case is dealing with a question which resembles those the chemist has to explain.

"Had I to play at that foolish game," some one may say, "I would open the parcel and look in; and with a little rummaging I would soon find out whether the other player had changed the contents of the parcel or not." But however keen your eyesight you might easily miss a few grains of pepper among the tea; and although your sense of smell is very delicate a fraction of a grain of cinnamon might escape your nose And when you play the real game, the chemist's game, the parcels you are set to rummage are either very hard to open, or they have a way of falling to pieces while you are looking at them; and if you succeed in opening the parcels and taking out the contents, the things you arrange in heaps according to their kinds are strangely different from the appearance of the things when they were mixed together in the parcels.

The illustration is crude; but it may help us a little now, and it will perhaps help us more at a later stage of our inquiries.

The box which contains the things the chemist has to deal with is the Earth. There are other boxes outside the earth, but the chemist has as yet only one instrument for opening the lids of these a little that he may peep in at the contents; that instrument, the spectroscope, enabled the chemist to see a certain kind of matter in the sun which was not known to exist in the earth, and which for that reason was called *helium*, but within the last year or two the chemist has been using the same instrument to search odd nooks and crannies of his earthly domain, and he has discovered that the solar matter he called helium exists shut up in some out of the way minerals that are found on the surface of the earth.

Let us turn back to the experiments wherein wood and sugar were changed into substances quite different from themselves by the action of heat. The results of these experiments proved, it was said that the compositions of the wood and the sugar were changed. What new substances then were formed when these things, wood and sugar, were heated? And what are the differences between the compositions of the new substances and those of the things from which these new substances have been produced?

When sugar is resolved into its simplest constituents these constituents are found to be three very different substances: one of these is *carbon*, a substance well known to everyone by the name of charcoal; another of the three substances is a colourless, odourless, gas to which the name *oxygen* is given, and the third is also a colourless, odourless, gas, but a gas that differs much from oxygen; to this gas is given the name *hydrogen*. From a determinate weight of sugar certain determinate weights of these three kinds of matter can be obtained; the weight of carbon, or the weight of oxygen, or the weight of hydrogen is less than the weight of the sugar from which the carbon, oxygen, or hydrogen is obtained; and the sum of the weights of carbon, oxygen, and hydrogen is equal to the weight of the sugar from which these substances are produced. By no process has it been found possible to obtain from a specified weight of carbon any substance different in properties from carbon and weighing less than the weight of carbon used; and what is true of carbon is true also of oxygen and hydrogen. These things carbon, oxygen, and hydrogen, can be changed into other things, but the changes are always effected by adding other substances to the carbon, hydrogen, or oxygen; in other words, the new substances obtained always weigh more than the carbon, the oxygen, or the hydrogen weighed; and when a new substance is formed by adding other things to carbon, oxygen, or hydrogen, the weight of carbon, oxygen, or hydrogen used, but no more than this weight, can always be obtained again from the new substance so formed.

These three kinds of matter, which are called carbon, oxygen, and hydrogen, respectively, are said to be the simplest substances into which sugar can be resolved; it would be better to say that these are the simplest substances into which sugar has been resolved. The word *simplest* is used as a convenient term to express the fact that no one has been able to separate carbon, or oxgyen, or hydrogen, into parts that are unlike one another; it is true that substances very unlike carbon, oxygen, or hydrogen are easily obtained from these kinds of matter; but no one of the processes whereby such substances are formed is a process of separation or sorting, for the new substance always weighs more than the carbon, oxygen, or hydrogen weighed, and the new substance is always formed by adding some other kind of matter to the carbon, the oxygen, or the hydrogen.

Wood, like sugar, is composed of carbon, oxygen, and hydrogen; but a specified weight of wood contains weights of these three kinds of matter different from the weights of them that are contained in a weight of sugar the same as the specified weight of wood; in other words the qualitative composition of wood is the same as that of sugar, but the quantitative composition of these two substances are different.

When sugar, or wood, is heated, new substances are produced: some of the carbon that was in the sugar makes its appearance as black charcoal in the vessel wherein the heating is conducted; gases are given off, some of which are combustible and some smell strongly, and these gases are composed of carbon, oxygen, and hydrogen, or of two of these substances.

Experiments with weighed quantities of salammoniac have proved that this substance can be resolved into two gases, one called *ammonia* (commonly known, when dissolved in water, as spirits of hartshorn), and the other called *hydrochloric acid gas* (commonly known, when dissolved in water, as spirits of salt). The weight of ammonia, or the weight of hydrochloric acid gas, that can be obtained from salammoniac is always less than the weight of the salammoniac from which these gases are obtained; and when salammoniac is formed by causing ammonia and hydrochloric acid gas to combine, the sum of the weights of these gases that disappear is exactly equal to the weight of salammoniac that is formed. But ammonia and hydrochloric acid gas are not the simplest constituents of salammoniac; for each of these gases can be resolved into two substances quite unlike itself. Ammonia can be separated into two parts, each very different from the other and both quite dissimilar from ammonia; one of those parts, or constituents, of ammonia is hydrogen—one of the gases that can be obtained from sugar—and the other is a colourless, odourless, very inert gas called *nitrogen*. Hydrochloric acid gas also can be separated into two dissimilar portions or kinds of matter; hydrogen is one of these, and the other, called *chlorine*, is a yellow, very badly smelling, suffocating, gas. The weight of nitrogen, and the weight of hydrogen, obtainable from a determinate weight of ammonia is less than the weight of ammonia that is separated into nitrogen and hydrogen: similarly hydrochloric acid gas yields less than its own weight of hydrogen, and less than its own weight of chlorine. Finally, the sum of the weights of nitrogen and hydrogen that can be obtained from ammonia is exactly equal to the weight of ammonia from which they are obtained; and the sum of the weights of hydrogen and chlorine that can be obtained from hydrochloric acid gas is exactly equal to the weight of that gas from which they are obtained.

No process is known whereby either nitrogen or chlorine can be resolved, or separated, into dissimilar kinds of matter: if a new kind of matter is produced from nitrogen, or chlorine, the new substance always weighs more than the nitrogen, or the chlorine, from which it has been produced; and the new substance is always formed by adding some other kind (or kinds) of matter to the nitrogen or the chlorine.

Nitrogen and hydrogen, then, are the simplest constituents of ammonia; and chlorine and hydrogen are the simplest constituents of hydrochloric acid gas. Salammoniac can be resolved into ammonia and hydrochloric acid gas; but the simplest constituents of salammoniac are the three gases nitrogen, hydrogen, and chlorine, fo ammonia can be separated into nitrogen and hydrogen, and hydrochloric acid gas can be resolved into chlorine and hydrogen.

We have then two classes of substances; those that have been separated into unlike parts or constituents, and those that have not been separated into dissimilar portions; it is convenient to speak of the latter as simpler than the former.

Iron belongs to the class of substances that have not been divided into dissimilar constituents, when iron is changed into something different from itself the change always consists in the adding on to the iron of some other substance, or some other substances. Iron is one of the relatively simple kinds of matter.

In the next chapter certain examples of changes of matter will be considered in some detail, with the object of becoming acquainted with the methods that are used in investigating those transmutations which are classed together as *chemical changes.*

CHAPTER III

THE CHEMIST'S CLASSIFICATION OF MATERIAL THINGS

ALL the wonderful changes that proceed in material things around us, and all the changes that can be produced in these things by man's device, are either occurrences wherein the composition, as well as the properties, of the matter affected, undergo modification, or they are events in which the composition of the matter dealt with remains unaltered although its properties are changed. Chemistry is concerned with those phenomena which are marked by change of composition accompanying change of properties; and the object of chemistry is to study those transmutations that occur simultaneously in the composition and properties of definite kinds of matter, and to express the results of this study in general statements which hold good in all particular cases, and which connect, or at anyrate suggest connections between, the chemical aspects of natural phenomena and the other parts of these phenomena. The chemical study of any occurrence presents two lines of inquiry; the compositions of all the substances that take part in the occurrence must be studied, and the properties of all these substances must be studied. It is on these lines that our examination of the chemist's dealings with nature must proceed. The chemical examination of any natural occurrence is an examination of only a part, it may be a small part, of the whole event; but the chemist is bound to make his part of the inquiry as complete as he can. Nature defies complete analysis; nevertheless, the student of each part of nature's working must do his best to take out the folds; remembering always that much will remain for the workers in other branches of natural knowledge, and, not forgetting, that when the men of science have completed their inquiries, there is need of the realising grasp of the man of imagination—the man who sees and can express his vision—to bind together the parts into a unity which satisfies.

All material things can be placed in one or other of two classes; they are either things like iron or things like wood: that is to say, they are either things which have not been separated into dissimilar parts, or they are things which have been separated into unlike portions. But chemistry does not deal with all material things; this branch of natural knowledge concerns itself with what I have called, on p. 34, "definite kinds of matter." It is sometimes said that chemistry deals with changes occurring in "homogeneous bodies." What is meant by these expressions, "definite kinds of matter," and "homogeneous bodies"? They are used to convey the same meaning, what, then, is their meaning?

You are handed a cup of coffee at the breakfast table. You sip a little to find whether there is sugar in it or not; your sense of taste detects the presence or absence of sugar. The coffee is too strong, you pour hot milk into it that the neutral taste of the milk may tone down the aromatic flavour of the coffee; and if you put in too much milk you remedy that by adding more coffee. Each ingredient of the beverage you are drinking—infusion in water of coffee beans, milk, and sugar—carries its own special properties with it, and retains these properties in the mixture you consume. You would certainly be surprised if the addition of a lump of sugar made the coffee bitter, or if pouring in milk deepened the colour of the liquid in your cup. A cup of coffee is not a "definite kind of matter"; it is not a "homogeneous body." It is made of, at least, three different substances, and each of these retains its own properties in the product of the mixture of them. A cup of coffee is a mixture. A chemist asked to examine this mixture would examine the composition and properties of the milk, the sugar, and the coffee beans, separately. "The liquid you drink," he would say, "has no distinct and precise properties of its own; one man takes his coffee *black*, another has his mostly all milk, a third can't drink coffee with sugar in it, and a fourth puts half-a-dozen lumps of sugar into a single cup: yet these different mixtures are all called coffee." The ordinary coffee-drinker builds up his beverage on a foundation of coffee-beans; and he is able to distinguish, by his sense of taste, the different parts of the building.

Now suppose a man is a connoisseur in coffee; he cannot drink his coffee unless it is made from freshly roasted beans; and, that the process may be stopped exactly at the right point, he roasts his beans each morning before breakfast. The roasting process brings about a deep seated and permanent change in the beans; light-coloured and nearly odourless things are changed into mahogany-brown and odoriferous substances; from somewhat insipid things are produced things whose taste is pleasing to the palate. As the chemical changes proceed in the roasting beans, the sense of smell enables the trained operator to follow these changes step by step. It is surely impossible that something with that all-penetrating odour was actually in the unroasted beans, and that the roasting is merely drawing out what was already there? The senses declare that new substances are being formed as the roasting proceeds. The fastidious coffee-drinker who roasts his own beans morning by morning daily carries out a process of practical chemistry, and every morning he impresses on the senses of the household the singular accuracy of the schoolboy's designation of that branch of science. It is true that the sense of smell does not enable an ordinary person to determine whether the odoriferous emanations from the roasting beans consist of several ingredients, differing in gradations of piquancy, or whether the smelling thing is one and undivided. But at anyrate a marked change, and a fairly definite change, is being brought about: the unroasted material is not a mixture of odourless beans and a smelling substance; the roasting undoubtedly calls into existence kinds of matter that were not there before.

Take another example. Beer is a mixture of many things; its chief constituents are water, the soluble parts of hops, fruit-sugar and other substances from malt, and alcohol. If a bottle of beer is distilled until about three-fourths of it has disappeared, and the vapour that comes off is condensed to a liquid, this colourless liquid contains all the alcohol that was in the beer. If the colourless liquid is distilled repeatedly, and the last distillate is boiled with burnt lime and then distilled again, almost pure alcohol is obtained. And it is possible to separate the small quantity of water that is mixed with this alcohol, and so to produce what is called "absolute alcohol." By taking advantage of certain properties of alcohol and water, respectively, the alcohol that is contained in beer can be separated from the water and the other ingredients of the beer. The alcohol retains its own properties in the mixture of alcohol and other things we call beer. The beer can be sorted out, by distillation, into unlike parts of which alcohol is one; and a mixture of these parts has the properties of beer. But by no mere sorting process can alcohol be separated into things unlike itself: nor can alcohol be produced by mixing other things. It is true that alcohol has been separated into unlike parts or constituents; it has been separated into carbon (a substance well known as charcoal), and hydrogen (a very light, colourless, inflammable gas), and oxygen (also a colourless gas, but not inflammable). But the process whereby these kinds of matter are obtained from alcohol is a process of breaking up, it is not a sorting out, like sifting coarser from finer sand, or an unravelling, like disentangling skeins of blue and yellow silk. By no process can carbon be removed from alcohol except by breaking up and disintegrating the alcohol. Alcohol cannot, by any stretching of the term, be called a mixture of carbon, hydrogen, and oxygen Alcohol is as definite and homogeneous a kind of matter as any of its three constituents; only it is possible to obtain from a definite weight of alcohol certain definite weights of carbon, hydrogen, and oxygen, such that, while the weight of each is less than the weight of alcohol used, the sum of the weights of the three is equal to the weight of alcohol used; whereas no one has succeeded in subjecting carbon, hydrogen, or oxygen to a process of disintegration, or simplification, similar to this.

Chemistry, then, is concerned with the changes of composition and properties that take place when one definite kind of matter is transmuted into other definite kinds of matter, or when several homogeneous bodies interact so as to produce other homogeneous bodies.

It is true that most of the definite kinds of matter with which the chemist has to deal are given to him mixed one with another. Pure water is a perfectly distinct substance; the properties of any portion, however small, of a quantity of pure water are identical with the properties of any other portion. But pure water is never found in nature; one may even say that no man has ever seen or handled absolutely pure water; it is an ideal substance, to which some specimens of highly purified water have nearly approached. Natural waters are complicated mixtures; but the proportion of impurities, that is, substances which are not water, in some kinds of lake waters, and in the rain that falls in places far from human habitations, is so small that such water may be spoken of in ordinary language as pure.

Again, the substances that are commonly used as fuel are mixtures, each of several distinct kinds of matter or homogeneous substances. Take for instance paraffin oil. If a homogeneous liquid is boiled in a flask with rather a long neck, a thermometer placed in the neck of the flask will register the same temperature as long as any boiling liquid remains in the flask. But if paraffin oil is boiled under these conditions, the temperature of the vapour that is given off is shown by the thermometer to change very considerably. By condensing to liquid all the vapour that comes off while the thermometer varies but slightly; then changing the collecting vessel, and receiving in it the liquid that distils over while the thermometer marks another small variation of temperature; then again changing the vessel; and so on: and by repeating these processes many times with each of the several portions of liquid in the collecting vessels:—by such a series of tedious operations, paraffin oil can be sorted out into many distinct portions, each of which is a homogeneous liquid with its own distinct and characteristic properties.

Once more, the rocks, clays, sands, and minerals that are spoken of under definite names in mineralogical or geological books are mixtures, and some of them are very complicated mixtures. The geologist classifies rocks under such names as *slate*, *schist*, *felspar*, *mica*, *quartz*, *sandstone*, *limestone*, and the like; and a classification of this kind is sufficient for his purposes. All the rocks called *schist*, for instance, are more like one another to the geological eye than they are like any other rocks; when the geologist has divided the schists into such subclasses as *mica schist*, *hornblende schist*, and *chlorite schist*, he has carried the sorting process far enough for the purpose of distinguishing broadly one variety of rock from another, so that the story of the formation of masses of rock may be stated in intelligible terms. But if the chemist has to deal with such mixtures of definite substances as different kinds of *limestone*, his first business is to pick out, by some suitable device or appropriate machine, the definite kinds of matter of which each variety of limestone is composed, and his next business is to find out how far he can carry the process of simplification of each of these definite kinds of matter. When he has determined which of those simplest kinds of matter whereinto he has succeeded in disintegrating all material substances enter into the composition of each distinct and definite substance obtained from the various limestones, and when he has determined the quantity of each simplest kind of matter in a definite quantity of each homogeneous substance sorted out of the limestones, then he has performed his task so far as the composition of those mixtures that the geologist calls limestone is concerned.

Although the chemist does not begin his proper work until the mixtures that are found in nature have been sorted into their distinct and homogeneous components; although, in other words, chemistry is not concerned, strictly speaking, with mixtures, but only with those definite kinds of matter the smallest parts of which that can be obtained by any kind of sorting process which does not involve the breaking up of the substance are identical in properties with one another; although this is true, nevertheless the chemist is so often obliged to preface his proper work by acting as a sifter of mixtures, that I should like to say a little more on the meaning of the terms *mixture* and *homogeneous body*, and to illustrate the intermingling of these two classes of substances in some well-known material of everyday life.

I shall try to illustrate this point of fundamental importance by sketching the processes whereby beer is manufactured. Malt is made by causing germination to begin in barley, and then stopping this process by heating in kilns. A definite substance called *diastase* is produced in the germinating barley, and this substance is able to convert starch into sugar. The malt is crushed and agitated with water in tuns, at a temperature of 50° to 70° C. [120° to 170° F.]. The liquor that is drawn off is known as *wort*; it is rich in sugar produced by the action of diastase on the starch of the barley. The wort is now boiled with hops, whereby some of the bitter substances in the hops go into solution and impart their flavour to the wort The liquor is then cooled rapidly, a little *yeast* is added to it, and it is kept at the temperature which experience has shewn to be most favourable to the change of sugar, by the action on it of yeast, into alcohol and carbonic acid gas. The fermented liquid is stored in closed barrels or bottles; and a change, called secondary fermentation, goes on slowly, and produces a very little more alcohol, and a small quantity of carbonic acid gas which collects in the liquid, and, by escaping when the barrels, or the bottles, are opened, causes brisk effervescence.

The principal *chemical changes* that take place in the making of beer are the conversion of starch into sugar by the action of diastase, and the transmutation of sugar into alcohol and carbonic acid by the action of yeast. In these changes, definite kinds of matter are converted into other definite kinds of matter; and each change of one homogeneous body into other homogeneous bodies takes place under definite conditions. The homogeneous kinds of matter chiefly concerned in the processes are starch, sugar, alcohol, and carbonic acid gas. Starch, sugar, and alcohol have been separated each into three dissimilar constituents called carbon, hydrogen, and oxygen, respectively; and carbonic acid gas has been separated into carbon and oxygen. But no one of those three homogeneous bodies, which are the constituents of starch, sugar, alcohol, and carbonic acid gas, has itself been disintegrated into unlike portions. These three definite kinds of matter are the simplest constitiuents of the other four definite kinds of matter. A definite quantity of any one of the four things, starch, sugar, alcohol, or carbonic acid gas, is always composed of fixed and unalterable quantities of its simplest constituents. For instance, 100 lbs. of pure fruit sugar are always composed of 40 lbs. of carbon, $53\frac{2}{5}$ lbs. of oxygen, and $6\frac{3}{5}$ lbs. of hydrogen; and 100 grains of any specimen of pure carbonic acid gas are always composed of 27·27 grains of carbon and 72·73 grains of oxygen. Moreover, if pure fruit sugar were completely changed into alcohol and carbonic acid gas, and into these substances only, 51·1 oz. of alcohol, and 48·9 oz. of carbonic acid gas would always be obtained from 100 oz. of the fruit sugar; and if the whole of the sugar were not changed into alcohol and carbonic acid gas, the weights of the three substances, sugar, alcohol, and carbonic acid gas, concerned in the change would always be related in the proportion of the numbers 100 : 51·1 : 48·9, or of whole multiples of these numbers.

These definite chemical changes—namely, the conversion of starch into sugar, and the transformation of sugar into alcohol and carbonic acid gas--proceed during the making of beer in a liquid which is essentially a mixture of very many substances; nevertheless the chemical changes take place under certain conditions, the chief of which are the presence of diastase in one of the changes, the presence of yeast in the other, the presence of water in both, and the maintenance of a suitable range of temperature. The amount of water added for each ton of malt varies in different breweries; one specimen of barley is richer in starch than another; one kind of hops contains more of the bitter substances that flavour beer than another kind; and the German brewer carries on the fermentation process at a lower temperature, and more slowly, than the English brewer. Variations in the quantities of the main constituents of beer are allowable, provided these variations are kept within limits; and variations in the conditions under which the chemical changes proceed may also be made, but only within a limited range. Beer is a mixture; but it is a mixture of not very varying quantities of certain definite kinds of matter, the presence of each of which is essential, in quantities that vary considerably of other kinds of matter, some of which are definite substances and all of which can be resolved into definite substances. The art of brewing is not accomplished by mixing certain things and calling the mixture beer. It is a much more difficult business than that. Certain things must be mixed, and the conditions must be arranged so that some, but not all, of the constituents of the mixture shall react to produce fairly fixed quantities of certain other perfectly definite things;

and if the proper limits of the conditions are passed, the new things, by the production of which in due quantities wort is transmuted into beer, will not be formed, but other things will be formed instead, and the final result will be a liquid which, whatever it may be called, is emphatically not beer.

Many people like to drink their beer from pewter. As they pour the beer into the pewter mug, they are pouring a liquid which is the product of many chemical changes into a vessel made by mixing, not chemically combining, two metals. Pewter is made by melting a mixture of about four parts of tin with one part of lead. There is no change into new kinds of matter. The properties of the pewter are, on the whole, the mean of the properties of the lead and tin of which it is composed. The colour is brighter than the colour of lead, but duller than that of tin; pewter is harder than lead, but softer than tin. From a knowledge of the properties of lead and tin one could predict, very fairly well, the properties of the mixture of these metals called pewter. Moreover different specimens of pewter contain different relative quantities of lead and tin; one specimen may contain as much as 90 parts of tin per hundred of pewter, while another contains less than 70 per cent. of tin. Pewter does not belong to the class of 'definite kinds of matter' or 'homogeneous bodies'; by processes which are essentially sorting or disentangling processes, the constituents of pewter, lead and tin, could be obtained from pewter.

Very many manufacturing processes are based on definite chemical changes; but the products turned out in almost every branch of the chemical industries are mixtures of several definite kinds of matter. For this reason it is generally easy for a chemist to lay down what may be called the theory of a chemical manufacture; but it is very difficult to apply the theory to the complicated, semi-chemical, conditions that prevail in the factory.

In trying to understand chemical occurrences, and to arrive at general statements which shall express what holds good in all those transformations of matter wherein composition and properties change together, we must confine our attention to the homogeneous bodies that are concerned in the events we study; we must simplify the natural occurrences by deliberately cutting out all those parts of them which have not to do with definite kinds of matter.

It was said (p. 34) that all material things may be arranged by the chemist in two classes: they are either things like iron or things like wood; that is to say, they are things that, like iron, have not been separated into unlike parts, or they are things which, like wood, have been separated into dissimilar portions. We now know that the class of wood-like things must be divided into two sub-classes: things, the composition of which is variable within limits, and the separation of which into unlike constituents is effected by sorting processes which do not involve the complete disintegration of the things themselves; and things whose composition is always absolutely the same, and from which unlike portions can be obtained only by breaking up and destroying the things themselves. Wood is an example of the first of those sub-classes, and sugar is an example of the second. Wood is a mixture of many homogeneous bodies, and different specimens of wood differ in the relative quantities of their component substances; sugar is a particular homogeneous body, and all specimens of pure sugar have exactly the same composition. Chemistry is concerned with certain changes occurring among homogeneous bodies: and these bodies are either like iron, in that however much they are divided the particular properties of all the parts are identical; or they resemble sugar, in that they can be separated into simpler homogeneous bodies whose special properties are different from those of the more complex homogeneous bodies out of which they have been taken.

It is convenient to give class-names to the two kinds of homogeneous bodies. Those that are like iron are called *Elements*, those which resemble sugar are named *Compounds*.

We have now arrived at this point. All material substances either have, or have not, been resolved, or separated, into unlike portions, that is to say, every kind of matter belongs to one or other of the classes

ELEMENTS. NOT-ELEMENTS.

But some of those kinds of matter which are not elements, which have been separated into unlike portions, are perfectly definite homogeneous bodies that cannot be sorted out into their dissimilar constituents; and other kinds of matter belonging to the class not-elements are mixtures of homogeneous bodies, and they can be sorted out, or disentangled, into their dissimilar constituents. We now express our scheme of classification in this way;

Elements   Not-Elements
Mixtures   Compounds

It is evident that the same result is arrived at by the following arrangement of all material substances.

Mixtures   Not-Mixtures
Elements   Compounds

Chemistry deals with certain changes that take place among Elements and Compounds; and these changes are those in which both composition and properties are affected.

Turn back for a moment to the illustration, used in last chapter, of the game with a box containing a great many different substances (see p. 26). Nothing is to be brought into, or to be taken out of, the box; but the contents of any special parcel in the box may be changed. One of the players examines the contents of a parcel; the other player then takes something out of the parcel, or puts something into it, or does both of these acts, or does not change the contents of the parcel; and the first player has to find out which of the four possible moves has been made by his opponent. All the substances in the chemist's box are either elements or compounds: as his box is the earth, or a portion of the earth, it contains a vast number of things which are mixtures of elements or compounds; but before the game really begins we must suppose that these mixtures have been sorted into the compounds, and in some cases into the element , of which they are composed. The first thing to be done by the chemist would be to determine the quantity of each individual element in the box, and also in the selected parcel; and the next thing would be to resolve every compound in the box and every compound in the parcel, into its elements, and to determine the quantity of each one of the various elements that could be obtained from a definite quantity of each particular compound. To do these things would involve the constant and accurate use of the balance. Having done these things the chemist would know the quantity of each element that was present, uncombined with other elements, in the box, and in the parcel; and he would also know the quantity, and the quantitative composition in terms of elements, of every compound in the box and in the parcel. When the opponent had made his move, the chemist would again determine the quantity of each uncombined element, and the quantity of each compound in the parcel, and in the box; and he would follow this by making a determination of the quantitative composition of every compound, and expressing the results in terms of the elements that compose the compounds. He would then be able to state exactly what the opponent's action had been. He might say, for instance, "Here are the contents of the parcel before, and after, your play." (See over page.)

BEFORE.

Total weight of substances composed of 130·405 grains

Element A 4·0 grains
Element B 5·5 ,,
Compound X 120·34 ,, made of
100·21 grains *Element C*
20·13 ,, *Element D*
120·34

Compound Z 0·565 grains made of
0·232 grains *Element E*
0·112 ,, *Element F*
0·221 ,, *Element G*
0·565

130·405

AFTER.

Total weight of substances composed of 150·0 grains

Element B 5·5 grains
Element D 20·13 ,,
New Compound M 104·322 ,, made of
4·0 grains *Element A*
100·21 ,, *Element C*
0·112 ,, *Element F*
104·322

New Compound P 20·048 grains made of
0·232 grains *Element E*
0·221 ,, *Element G*
19·595 ,, *New Element H*
20·048

150·0

"These results show that you have rearranged the combinations of some of the elements; you have caused element *A* to enter into combination with other elements that were present originally in compounds which you have split up; you have taken the element *D* away from those elements with which it was combined; and you have brought a new element, *H*, into one of the new compounds that have been made. It is evident that the contents of the box outside the parcel have been changed, by removing 19·595 grains of the element *H*, and bringing that inside the parcel. Now I know that there was none of that element *H* uncombined with other elements in the box; therefore, you have broken up some compound or compounds of *H*. What you have done I can find out, exactly, by an examination of the contents of the box similar to the examination I have made of the contents of the parcel."

This illustration conveys some notion of the kind of work chemists have done, and are doing, in elucidating the compositions of material things. The labour is very great, and it is made a little tedious by the sameness of many of the operations. But new difficulties are met at every step; and the efforts and ingenuity that are needed to overcome these difficulties give freshness and interest to this part of the work of chemists. It should be remembered that the study of composition is only a part of the study of chemistry; for the object of chemistry is to connect definite changes of composition with definite changes of properties; and to generalise the results of that twofold study in statements which express the essential characteristics of every case of chemical change, in statements, that is to say, which are general laws.

About seventy different kinds of matter are known at present, no one of which has been separated into unlike parts by any process to which it has been subjected; these are the elements by the combination of which an innumerable array of compounds is formed in nature and in the laboratory. Considering that the list of elements is much larger to-day than it was thirty years ago, it is almost certain that new elements will be discovered as the instruments of chemical research become keener and more delicate. But at present it may be said that the compounds which we find in rocks, soils, and waters, in living things, in the air, and generally, in or on the earth, are formed by the union of two or more of these seventy elements. And by bringing together elements and compounds in the laboratory under conditions different from those which prevail in ordinary nature, the chemist has built up thousands of compounds the study of which has thrown floods of light on the problems of what may perhaps be called natural chemistry.

We cannot say of the elements that they are unchangeable; for we know that some substances which the chemists of half a century ago called elements, because they could not get out of them anything different from themselves, are now classed among compounds, because more powerful instruments of research have enabled the chemists of to-day to separate these substances into parts, each unlike the original, and one unlike another. A similar fate may befall the kinds of matter we call elements to-day. But until a homogeneous body has been disintegrated into dissimilar portions it must remain in the list of elements. Although we cannot apply the expression *unchangeable* to the elements, yet we may speak of them as *unchanging*; for, so far as our experimental evidence goes, none of them is ever broken or shattered. They are the building stones of the chemical architect; the stones wherewith he fashions many strange edifices that are totally unlike the materials used in their erection. You do not see the individual stones in the structures which the chemist builds; because the buildings are so unlike what you would expect from looking at the unbuilt materials, and because the joints are so delicately finished, and the stones so truly fitted, that your eyesight is not keen enough to detect the separating lines. But all the buildings can be taken to pieces; and when this is done the original building stones are recovered absolutely unchanged.

In chapter I. I quoted from an alchemist who said; "There abides in nature a certain form of matter which, being discovered and brought by art to perfection, converts to itself, proportionally, all imperfect bodies that it touches." I shall conclude this chapter by quoting from a great living chemist. "In chemistry we recognise how changes take place in combinations of the unchanging."

CHAPTER IV.

THE COMPOSITION OF HOMOGENEOUS BODIES.

CHEMICAL changes are those wherein elements combine with elements to form compounds; or elements interact with compounds, or compounds react with other compounds, to produce new arrangements of elements. In every one of these changes, in every material change indeed whether it be chemical or not, one thing remains unchanged; the total quantity of matter that is concerned in the change is the same at the end, as it was at the beginning, of the process. When sulphur is burnt in a stream of air, and the gaseous oxide of sulphur that is produced is brought into contact with a sufficient quantity of another gaseous oxide called nitrogen dioxide, and a sufficient quantity of vapour of water, and the acid liquid formed by these processes is evaporated and then frozen, the quantity of pure sulphuric acid that is obtained is greater than the quantity of sulphur that was burnt; but it is greater by exactly the sum of the quantities of oxygen and hydrogen that have been removed from the nitrogen dioxide and the steam which took part in the completed change. Other compounds besides sulphuric acid are formed in this chemical process; and the sum of the weights of all these compounds is exactly equal to the sum of the weights of the elements sulphur and oxygen and the various compounds that reacted to produce the new compounds.

When salt is heated with sulphuric acid, and the salt cake that is one of the products of this reaction is mixed with coke and lime and strongly heated, and the solid product so obtained is lixiviated with water and evaporated, crystals of washing soda are produced. Various other compounds besides washing soda are formed in this cycle of changes, and the sum of the weights of all the compounds that are produced is exactly equal to the sum of the weights of the elements and compounds that have interacted to produce them

The *law of the conservation of mass* is the name given to the statement that the total quantity of matter or, as it is generally said, the total mass of matter concerned in any material change is the same at the end as it was at the beginning of the change. This law is the foundation of the science of chemistry. The recognition of this law has changed chemistry from an interesting recreation into an exact, and much more interesting, science. The law is one of the outcomes of innumerable observations which, carried on for centuries, have become gradually more and more accurate. The truth of the law of the conservation of mass is assumed to-day in every chemical inquiry; and the assumption is justified by the results of every chemical inquiry. Whatever new compounds are produced by rearranging collocations of elements, in whatever startling and unlooked for ways the properties of the new compounds differ from those of the compounds, or the elements, which reacted to produce them, the total quantity of matter in the products of these rearrangements is always found to be exactly equal to the total quantity of matter in the material system before the rearrangements began.

It might be urged that the fact that chemical change is almost invariably accompanied by change of weight negatives the statement which has just been asserted to be a natural law. For instance, when iron rusts, the rust weighs more than the iron did; when sugar is heated, the charred sugar weighs less than the sugar weighed before it was heated; less than a ton of pig-iron is obtained from a ton of ironstone; and so on. But in every one of these changes something is concerned besides the things which have been weighed: iron rusts by taking oxygen from the surrounding air, and rust is composed of iron and oxygen; some of the products of heating sugar escape as gases; when ironstone is reduced in the blast-furnace some of the constituents of the ore react with the fuel to form gases which escape, and some enter into union with the lime that is thrown into the furnace and form slag. If every substance that takes part in a chemical change is weighed, and everything that is produced in the change is weighed, then it is always accurately true that no change occurs in the total weight of the matter concerned.

We cannot destroy, nor can we create, a single particle of matter; we can only alter the distribution of the various kinds of matter.

What kinds of things are those seventy elements which can be put together so as to produce a vast array of different compounds? All the metals are elementary substances; among the most common we have copper, gold, iron, lead, mercury, silver, tin, zinc, and aluminium which is now coming into use; among rarer metals may be mentioned arsenic, antimony, bismuth, cobalt, nickel, and platinum; and there are some forty other elements which belong to the class of metals. The four fairly common substances, carbon, iodine, phosphorus, and sulphur, are elements; the purest form of carbon found native is the diamond. Seven elements are gases under ordinary conditions of temperature and pressure. Five of the seven are colourless and odourless: one of them, hydrogen, is inflammable, and it is the lightest kind of matter known to us; another, oxygen, is a gas in which any burning body burns brilliantly and rapidly; the third, nitrogen, is neither inflammable nor a supporter of combustion, it is sluggish and combines with other elements only when greatly provoked; the other two colourless elementary gases, argon and helium, were discovered but the other day; these persistently refuse to combine with any other kinds of matter. Two of the gaseous elements are yellowish green; they are chlorine, which smells abominably, and fluorine, which is the most eager of all the elements to enter into union with others. Two elements are liquids at ordinary temperatures; these are mercury (one of the metals), and bromine which is a red liquid with a smell even more disagreeable and more irritating than the smell of chlorine. Three bodies which are solids complete the list of elements known to-day: boron is an element separated from borax; silicon is the characteristic element of the clays; and selenion is chemically like sulphur.

Seven metals seem to have been known to the ancients; namely, copper, gold, iron, lead, silver, tin, and zinc; sulphur has also been known since early times. The alchemists were acquainted with antimony, arsenic, bismuth, and mercury; phosphorus was discovered towards the end of the seventeenth century. The other elements have been discovered within about the last 120 years, and most of them in the present century. Great activity in separating new elements was shown by Sir Humphry Davy in the early years of this century, from 1808 to 1810 he isolated half-a-dozen new metals. In the twenties of the century five or six new elements were isolated by the great Swedish chemist Berzelius; eight or nine were discovered between 1815 and 1865. About ten new elements have been added to the list since 1865; four in the last ten years, and two of these since the end of 1894.

The names of some elements have been given to express a characteristic property of those elements. For instance: hydrogen, the water-producer; oxygen, the acid-producer; bromine, the evil-smelling substance; chlorine, the yellow one; phosphorus, the light-bearer. The names of other elements have been derived from the names of the minerals from which those elements were obtained, or from the names of the places where these minerals were found. For instance: beryllium, obtained from beryll; ytterbium, separated from a mineral found at Yetterby, in Sweden; boron, the characteristic element of borax. Two elements have been named to commemorate their discoveries by a Frenchman and a German respectively; these elements are gallium and germanium. The names of several elements are purely fanciful · for instance; tellurium and selenion, the earth and the moon; tantalum and niobium, from Tantalus and Niobe his daughter; mercury; vanadium, from a Scandinavian deity called Vanadis; cobalt and nickel, from "Kobold," a sprite, and "Kupfer-nickel" which was the name given by the mediaeval German miners to a mineral like copper ore from which no copper could be obtained.

Those sixty-five or seventy distinct kinds of homogeneous bodies, no one of which has been broken up into parts that are unlike one another, or unlike the original substance, are the building stones of the earth, and, so far as we can tell, of the other stars also. Compounds, which are themselves also definite substances, which have definite properties, and the composition of each of which is always exactly the same, are produced by the intimate union of two or more elements; and mixtures of compounds, with here and there mixtures of elements, or of elements and compounds, form the solid crust of the earth, and the waters that rest on this solid crust, and the gaseous envelope that surrounds it, and the living things that move on the earth, or fly in the air, or swim in the waters. The number of compounds that might be produced by combining different quantities of two, three, four, or a larger number of the elements is infinite. It has been calculated that if the whole population of the world were to devote their days and nights to dealing cards for hands at whist, they would not have exhausted one one-hundred-thousandth part of the possible deals after occupying themselves entirely at the task for one hundred million years. The chemist's pack contains about seventy cards; how many deals will be made before the combinations are exhausted? To make all the possible combinations would surely "exhaust time and encroach upon eternity."

The study of chemistry is certainly not lacking in variety.

Re-arrangements of elements are taking place every moment in our own bodies, and in animate and inanimate objects outside ourselves. Every breath of air drawn into the system supplies oxygen, which interacts with compounds of carbon, hydrogen, oxygen, and nitrogen in the body to produce new compounds of these four elements; some of these new compounds react with other compounds in the system to form more complex, but perfectly definite, collocations of elements, and some are removed from the system in the breath we expire, and in other ways. It is literally true that in the millionth fraction of every second millions of millions of living organisms are breaking down definite groups of definite quantities of the four elements carbon, hydrogen, oxygen, and nitrogen, and as innumerable an array of living things is building up definite arrangements of fixed quantities of these same elements. To the sound of the going of those silent changes the ear of the man of science is attuned to listen; and the sounds are harmonious, and there is rhythm through them all. The history of changes like those infinitely minute ones which are conducted on a vast scale can be traced, in a broad and general way, in the crust of the earth. The general tendency of the chemical changes that have taken place as the earth has grown older has been towards the formation of more complex, from less complex, compounds. This process seems to have been carried to completion, or nearly to completion, in the moon. There, chemical action appears to have stopped, or, at anyrate, to have become very sluggish, there, the elements have probably all combined into complex collocations; and the cessation of chemical changes seems to be accompanied by the absence of life.

Whether the manifold transmutations which take place in the combinations of the elements occur in the earth's crust, or in living things on the earth, or whether they are brought about by human agents, on a small scale in the laboratory, or on a large scale in manufacturing industries, all these changes follow certain general lines, and the results of all of them can be expressed, so far as the compositions of the thousands of compounds are concerned, in general statements which we call laws.

One law has been stated already; the law of the conservation of mass. This law—in no material change, or cycle of changes, is there any change in the total quantity of matter concerned in the operations—is taken as true in all chemical and physical investigations.

I have compared the processes whereby compounds are produced to building operations, the elements being the building stones and the compounds the finished buildings. The illustration may be carried further. Suppose that a chemical builder is trying to construct edifices with certain elements. He soon discovers that he must work under limitations. He cannot use any quantities he chooses of the different elements; the blocks of each building stone with which alone he can build are all exactly the same weight, and there is a fixed and unalterable relation between the weights of those pieces of the different building stones wherewith he is allowed to construct his buildings. It is as if a builder found each variety of stone he intended to use cut into blocks, any one of which weighed exactly the same as any other, but the blocks of one kind of stone weighed less, or more, than those of any other kind; and as if, when the builder wished to use a portion of a block, he found that not one of the blocks of any variety of stone could be broken. The chemical builder must use whole blocks of each elementary building stone; if one block of this or that element is not enough, he may try two, or three, or any number of, blocks; but he cannot divide even a single block into pieces, nor can he find even one block of any element which differs by the fraction of a grain in weight from the other blocks of the same element. Suppose the chemical buildings are constructed from the three elements hydrogen, carbon, and oxygen: a vast number of different compounds has been produced by changes in the combinations of these three unchanging things; but the quantities of the three elements that are combined in any one of these compounds are always related to one another in the proportion of one part by weight of hydrogen to twelve parts by weight of carbon to sixteen parts by weight of oxygen, or in the proportion of whole multiples of these three numbers (I am using round numbers to obviate very small decimals; the more correct numbers are 1 : 11·97 : 15·88).

Suppose the chemical builder gets annoyed at these limitations. He heaps together large, indefinite, masses of the three elements he is working with; and subjects the mixture to the action of very energetic reagents; for he is determined to bring in art to correct nature. But his art is a part of nature, and nature wins. Suppose a dozen compounds of the three elements are produced; the weights of hydrogen, carbon, and oxygen in each compound are still related to one another in the proportion of 1 : 12 : 16, or in a proportion expressible by whole multiples of these numbers. Suppose the result of the impatient chemist's manipulations has been a mixture of several compounds of hydrogen, carbon, and oxygen, with two compounds of hydrogen and oxygen, two of carbon and oxygen, and half-a-dozen compounds of hydrogen and carbon: every compound of the three elements contains weights of hydrogen, carbon, and oxygen related as represented by the expression n 1 : m 12 : p 16, when n, m, and p are whole numbers (generally small whole numbers varying from 1 to about 8); each of the two compounds of hydrogen and oxygen contains these elements united in the ratio of one part by weight of hydrogen to sixteen parts by weight of oxygen, or of a whole multiple of one part by weight of hydrogen to a whole multiple of sixteen parts by weight of oxygen; the ratio of the weights of carbon and oxygen in both the compounds that have been formed of these two elements is that of 12 to 16, or of a whole multiple of 12 to a whole multiple of 16; and the weights of hydrogen and carbon in each of the several compounds of these two elements that have been formed are related to one another in the ratio *n* 1 : *m* 12, where *n* and *m* are again whole numbers. Some portions of the elements which the eager experimenter threw into his mixing pot may remain uncombined, and some portions of them may be driven away from the other portions and sent wandering through space.

The impetuous chemical builder finds that his edifices cannot be constructed entirely according to his own fancy; he must work under the limitations imposed on him by the nature of his materials.

The illustrations given in the preceding paragraphs contain in themselves all the laws of chemical combination by mass; but it may be well to express these laws in more precise form. Those statements regarding the quantities of elements that react chemically which express what holds good in all chemical processes are generally divided into three parts; one part is called *the law of fixity of composition*, another *the law of multiple proportions*, and the third *the law of reciprocal proportions*. It is better however for our purpose to express these three laws in one statement, and to word that statement so that it may include what is universally true regarding the quantities of compounds, as well as regarding the quantities of elements, that interact chemically.

The quantity by weight of each element which takes part in any chemical reaction between elements, or between elements and combinations of elements, can be expressed by a certain fixed number, or by a whole multiple of that number.

And *the quantity by weight of each compound which takes part in any chemical reaction between compounds, or between elements and compounds, can be expressed by a certain fixed number, or by a whole multiple of that number.*

This fundamental law of chemical combination may be put in other words, as follows.

To every element there is attached a fixed number; and these fixed numbers express the smallest quantities by weight of the elements that interact chemically. If the quantities by weight of the elements that react in any special case are not expressed by the fixed numbers of those elements, then the reacting quantities are expressed by whole multiples of those fixed numbers. And what is true of elements holds good also for compounds. The quantities by weight of all compounds that interact chemically are expressed by certain fixed numbers; and if more than this quantity of any compound reacts, then the reacting quantity by weight is twice, or three times, or four times, or to put it generally, a whole number of times, more than the quantity expressed by the fixed number of that compound.

The law which has been stated is generally called *the law of combining weights*, in so far as it applies to elements; because it is customary to speak of the quantities by weight of elements which, or whole multiples of which, take part in chemical changes, that is, the quantities by weight that are expressed by what I have called the fixed numbers attached to the elements—it is customary to speak of these quantities as the *combining weights* of the elements. If this expression is used the statement of the law as far as elements are concerned may be put in fewer words: for it will run thus:—

Elements react in the ratios of their combining weights, or of whole multiples of their combining weights.

Inasmuch as the quantity by weight of a compound that is expressed by the fixed number attached to that compound that is, the quantity which, or a whole multiple of which, reacts chemically with other compounds or with elements—is often referred to as the *reacting weight* of the compound, the law which has been stated may be called *the law of reacting weights*, in so far as it applies to compounds; and with the help of the term 'reacting weight' the expression of the law as far as compounds are concerned may be put in fewer words, as follows:—*Compounds react in the ratios of their reacting weights or of whole multiples of their reacting weights.*

The system of shorthand used by chemists is based on the law of combining and reacting weights. Instead of always writing the name of an element, the first letter of the name, or the first and another letter, is used as a symbol for that element; thus C stands for carbon, Cr for chromium, B for boron, Be for beryllium, and so on. The symbols of seven of the metals that have been known for many centuries are derived from the Latin names of these metals; Sb = antimony (*stibium*), Cu = copper (*cuprum*), Fe = iron (*ferrum*), Pb = lead (*plumbum*), Hg = mercury (*hydrargyrum*), Ag = silver (*argentum*), and Sn = tin (*stannum*). The symbols K and Na are used for the metals potassium and sodium, respectively. The symbol K seems to be derived from the word *al-kali* (the ashes) applied for many centuries to the ashes of plants, from which substances the metal was obtained; (these ashes were also called *pot-ashes*, hence the name given to the metal). The symbol Na is probably derived from the word *natron*, which was applied in the Middle Ages to what seems to have been impure soda. In this case, as in that of potassium, the name (at least the English name) of the element has been derived from the name commonly given to the substance from which the element was isolated, and the symbol has been taken from an older name for the same substance.

Each symbol has a quantitative signification: thus C represents one combining weight of carbon, that is 12 parts by weight of carbon; Fe means 56 parts by weight of iron, that is one combining weight of iron, and so on. The compositions of compounds, both the qualitative and the quantitative compositions, are expressed by writing side by side the symbols of the elements that compose the compounds, and attaching small figures to these symbols to indicate how many combining weights of each element are combined in that weight of the compound which is expressed by the formula; it is customary to speak of the *formula* of a compound and the *symbol* of an element. For instance, water is composed of hydrogen and oxygen, and always of weights of these elements united in the ratio of 1 : 8. Now the combining weight of hydrogen is one (it is the standard substance to which other combining weights are referred), and the combining weight of oxygen is 16; the symbol H means one part by weight of hydrogen, and the symbol O means 16 parts by weight of oxygen. The composition of water then is expressed by the formula H_2O. This formula tells that the compound represented is composed of hydrogen and oxygen, and that 18 parts by weight of the compound are composed of 2 parts by weight of hydrogen and 16 parts by weight of oxygen. Take the formula for sulphuric acid, H_2SO_4. If a table of combining weights is consulted it is found that the combining weights of sulphur and oxygen are 32 and 16 respectively, that of hydrogen being unity. Now $(1 \times 2) + 32 + (16 \times 4) = 98$; hence we are told that 98 parts by weight of sulphuric acid are composed of two parts by weight of hydrogen, 32 parts by weight of sulphur, and 64 parts by weight of oxygen. One more instance. The formula which expresses the composition of cane sugar is $C_{12}H_{22}O_{11}$. Inasmuch as $C = 12$, $H = 1$, and $O = 16$ (that is, the combining weights of the elements carbon, hydrogen, and oxygen are 12, 1, and 16, respectively), it is easy to calculate the weight of cane sugar represented by the formula; this weight is evidently $(12 \times 12) + (22 \times 1) + (11 \times 16) = 342$. The formula expresses the composition of cane sugar in terms of the elements of which this compound is composed, for it tells that 342 parts by weight of cane sugar are composed of 144 parts by weight of carbon, 22 parts by weight of hydrogen, and 176 parts by weight of oxygen. It is of course easy to calculate the percentage composition of sugar, if it is desired to state the quantities of the three elements that compose it in that form.

The law of combining and reacting weights is the most important outcome of the investigation of the compositions of homogeneous bodies, considered apart from the examination of the properties of these bodies. To John Dalton belongs the signal honour of being the first to enunciate this fundamental law of chemistry. And it is most interesting to know that Dalton formulated the law (in the earliest years of this century) as a necessary deduction from the results of inquiries he was making into the physical properties of gases. He formed a theory of the constitution of matter the Daltonian atomic theory, which will be discussed briefly in a later part of this book (*see* Chapter VIII.)—to account for some of the physical properties of gases; he then deduced the law of the composition of homogeneous bodies from the postulates of that theory, stating the law in the language of the theory;

and then he performed a few experiments, and obtained results in keeping with those demanded by the theoretical deduction he had made. When the law had been announced, and its accuracy tested in a few cases by experiment, chemists soon recognised that a flood of light was thrown by the law on all the questions of composition with which they were especially concerned. Order and meaning were introduced into the accumulations of figures which represented the results of the analyses of compounds. It was discovered that many experimental verifications of the law had been made before the law was known, and that sufficient analytical results had been amassed to place the law on a fairly firm experimental basis.

The methods of quantitative analyses have become much more accurate since Dalton's time; and the results of all the hundreds of thousands of carefully executed analyses of compounds made since then have proved that the law of combining and reacting weights holds good accurately, and without any limitations or modifications, in every special instance of change in the compositions of systems of homogeneous bodies. This law is undoubtedly a law of nature.

The fact that the quantity by weight of an element, or of a compound, which takes part in any chemical change is always expressible by a certain fixed number, or by a whole multiple of that number, serves to emphasize, and to make more definite, the difference between elements and compounds on the one hand, and mixtures on the other hand. The composition of every specimen of any compound, stated in terms of the elements that have combined to form it, is always exactly the same ; and although a pair of elements may combine to form more than a single compound, yet, not only is the composition of each compound different from that of any other, and not only is the composition of each compound perfectly definite and quite unalterable, but it is also true that the quantities by weight of each of the two elements in the various compounds formed by the union of these elements are related in such a simple way that it is possible to express all these quantities as whole multiples of one and the same quantity. There is nothing even distantly approaching these facts to be found in the compositions of mixtures. Who shall determine how much sand, how much lime, and how much water must be mixed in order that the mixture may be used as mortar? The most superficial examination of the behaviours of different workmen engaged in making mortar convinces one that the makers of the mortars have no scruples in neglecting the law of combining and reacting weights. But neglect it as they like, the law holds good all the same. And it would be better for the builder, and much better for the tenant of the house, if this law, and other laws of chemistry, were consciously recognised and intelligently observed. For mortar-making, like nine-tenths of our manufactures, is the carrying out of several chemical changes in a medium that is itself a mixture. Perfectly definite quantities of lime and water combine to form slaked lime, itself a definite chemical compound ;

and after the mortar is set in the walls, carbonic acid gas is gradually absorbed by it from the air, and, combining with the slaked lime, slowly forms chalk; moreover, processes of chemical change go on very gradually for many years between the silica, which is a definite compound in the sand, and the slaked lime, and these changes produce silicate of lime which helps to bind the mortar into a compact mass.

Although the distinction between elements and compounds, on the one hand, and mixtures, on the other hand, is very marked, nevertheless the fact remains that most of the chemical changes that occur in our daily life—and there is no science that so "comes home to the bosoms and the business of men" as chemistry—occur between compounds, or between elements and compounds, that are so wrapped up and hidden in enveloping mixtures, that much detailed knowledge of chemical occurrences, and a considerable share of imagination, are required to remove the outer covering, and to see the essential changes that are taking place inside.

Now that we have attained a fairly definite conception of certain features of chemical change, let us, for a moment, contrast that conception with the picture which the transmutations of matter presented to the alchemist. The notion of distinct and definite kinds of matter, each with its own characteristic properties, was impossible in alchemical days, for the alchemists had no instruments for detecting small changes in the quantities of the matter which exhibited changes of properties. And until the changes which take place in the quantity of any portion of matter that is changing its properties have not only been detected, but also measured, it is not possible to say whether the compositions of portions of matter which show different properties are, or are not, identical. It is probably correct to say that the alchemists could not detect distinct differences in the compositions of portions of matter with different properties, because they had no instrument for determining, with accuracy, differences in the quantities of matter in two, or more, portions of matter; and it is also probably correct to say that the alchemists could not invent an instrument for detecting and measuring differences in the quantities of matter in various portions thereof, because they had no clearly-defined theory of the composition of material things. The construction of accurate balances led to great advances in chemical theory; and advances in chemical theory demanded, and called forth, great improvements in the art of the balance maker. The alchemical conception of the transformations of matter was radically wrong, because the alchemists did not attain, one might almost say that on account of their intellectual environment they could not attain, any clear notions regarding the compositions of different portions of matter. Divorced from the study of composition, the study of properties was obliged to base itself on vague analogies. Resting on that foundation, the determination and elucidation of properties *seemed* to grow apace, but there was no reality in the growth; the solid buildings, of which the vague alchemical vision was nothing but a mirage, lay far away, and many miles of dreary desert had to be passed before the gates of the city were reached. But a mirage means reality somewhere; and if the alchemists had not seen the vision, and followed it, we might have been wandering in the desert still.

Granting that the conception of definite composition could not be attained in alchemical times, we must surely admire the ingenuity, and applaud the subtlety, of the argument of the alchemists, whereby they thought they had established the possibility of transforming any material thing into any other thing, while at the same time leaving themselves an unchanging resting place amid the phantasmagoria of appearances. Matter was regarded by the alchemists merely as a vehicle for showing forth properties; they examined and recorded most extraordinary changes of properties; therefore they concluded that properties could be taken off, or put on to, any kind of matter, like clothes. A king in rags would receive no homage from his subjects, but clothe him in purple and fine raiment and he would again be recognised as the monarch. Lead, and copper, and iron, and tin were but different varieties of rags that hid the regal gold; but the rags might be removed in the furnace, or the alembic, and the poor naked king might be bathed in the "Water of Paradise," and the royal robes, brought on the wings of the phœnix, a bird of a most deep colour with a shining fiery hue, might be put upon him, and then he would appear in proper state and all would bow the knee before the king. But the alchemists felt that there must surely be an unchanging substratum beneath the ever-varying phenomena. Why was the thing they called gold sometimes so hidden by false appearances that ordinary people named it iron, or lead, or mercury, or zinc? The alchemists replied: because the gold has become contaminated, and rendered feeble and decrepit. Now their argument proceeded as impure things shrink from the touch of purity, and imperfect things recoil from things which are perfect, so it will suffice to touch the imperfect gold, that in his base estate is called by some other name, with the *One perfect matter*, and all the impurities will vanish and the gold will be seen to be gold indeed. This "One perfect matter," they said, is immutable; it is the essence that is hidden under thick coverings of imperfect matter. Some forms of matter will doubtless contain more of it than others, but as we do not know where it is chiefly concealed we must search for it everywhere. And the search is worth infinite pains; for when we have found *The one thing*, the smallest piece of it will suffice, not only to drag off the unworthy coverings from the regal gold, but also to remove all the trouble and sorrow from the world, and to transform this earth into a veritable paradise. For the alchemical quest was not merely the quest for gold. At its best it was more noble than that. It was an attempt, mistaken and hopeless, but not unworthy, to pass at one bound from trouble to peace, from unrest to quietness. In that quest alchemy failed; that pursuit chemistry has not attempted.

CHAPTER V.

THE STUDY OF PROPERTIES.

In chemistry we have to deal with the changes that take place when elements or compounds interact to produce other elements or other compounds. The composition of an element is expressed by the name of the element, for, so far as our experimental results have extended, any portion of an element is absolutely identical in characteristic properties with any other portion of that element. The composition of a compound is expressed in terms of the elements which by their union form the compound, and which can be obtained by breaking up the compound. The law of combining and reacting weights generalises the results of the study of composition, and expresses these results in a perfectly accurate form, which is applicable, without limitations or modifications, to every special case.

We must now turn to the second main division of chemical inquiry, and try to find out something about the properties of the elements and their compounds. We found that chemistry omits from the scope of its proper inquiry those kinds of matter that are neither elements nor compounds; we shall find that the strictly chemical examination of the properties of elements and compounds is limited to those properties which are exhibited when changes of composition take place. Speaking strictly, iron, or tin, or water, or salt, considered apart from other things or from the action of external agencies, presents no properties for the chemist to study; it is when the iron, or the tin, or the water, or the salt, acts on, and is acted on by, other kinds of matter (or is acted on by an external agency) so as to bring about changes of composition, it is only then that the properties of the iron, tin, water, or salt become interesting to the chemist. Chemistry studies elements and compounds in the act of changing. Inquiring into the properties of an element or compound, the chemist demands: What will it do when it reacts with other bodies? He must always ask, not only: What is this substance? but also: What has it been, and what will it be? Chemistry is interested in this or that definite kind of matter, not so much because of what it is now, as because its present condition is the result of changes in the past, and is the promise of changes in the future.

It is more correct to speak of the chemical *reactions*, rather than the chemical *properties*, of elements and compounds; for the word "reactions" emphasises that feature of the properties of these bodies which is essentially chemical.

As an example of the kind of inquiries that are made into the chemical reactions of compounds, let us consider, briefly, some of the reactions of water. When hydrogen is burnt in air, or in oxygen, water is produced; when an electric current is passed through a mixture of water and a little sulphuric acid, hydrogen and oxygen are obtained. When hydrogen is passed over heated red lead, or heated copper scales, or heated iron rust, water is formed together with lead, or copper, or iron. These qualitative facts furnish the bases of methods for determining the composition of water; and the results of such determinations are expressed by saying that important reactions of water are that, when hydrogen is burnt in oxygen, or when hydrogen is caused to withdraw oxygen from a metallic oxide, one part by weight of hydrogen combines with eight parts by weight of oxygen to form nine parts by weight of water, and that when water is acted on by an external agency which decomposes the water, nine parts by weight of water always yield one part by weight of hydrogen and eight parts of oxygen. When steam is passed over red-hot iron filings, the steam and the iron interact to produce hydrogen (one part by weight of hydrogen for every nine parts of steam that have reacted) and an oxide of iron; and steam reacts with several other metals similarly to the way in which it reacts with iron, that is to say, hydrogen and an oxide of the metal are produced. Water reacts at the ordinary temperature with sodium and potassium—the metals obtained from soda and potash respectively hydrogen is given off, and compounds of oxygen with hydrogen and sodium, or hydrogen and potassium, dissolve in the water which has not been used to react with the quantity of sodium or potassium employed. When a mixture of steam and chlorine (the evil-smelling yellowish gas got from common salt) is passed through a porcelain tube kept at bright redness, the steam and chlorine slowly interact to produce oxygen (eight parts by weight for every nine parts of steam that react) and hydrochloric acid which is dissolved in the excess of steam. When soda crystals are heated, water is given off in the form of steam; when the residue of calcined soda is dissolved in water and the solution is evaporated somewhat, crystals of washing soda form as the liquid cools. It is a reaction of water to combine with calcined soda to form washing soda; and it is a reaction of water to be driven out of this combination by heat. When cane sugar is heated, one of the things given off is water; but the production of this water is accompanied by the complete transformation of the cane sugar into other compounds. Water enters into the composition of oil of vitriol, but the properties of the water are entirely hidden in those of the acid, and water cannot be obtained from oil of vitriol except by processes which completely break up the acid.

As the study of the reactions of water proceeds, we find that very many of these reactions are similar to one or other of those which have been briefly described. These are: (1) reactions wherein water is produced by the combining of hydrogen and oxygen, one or both of these elements being in many cases first removed from combinations with other elements; (2) reactions wherein water is decomposed, hydrogen coming off, and oxygen remaining combined with the substance which has reacted with the water; (3) reactions wherein water is decomposed with evolution of oxygen, the hydrogen of the water remaining combined with the substance which has taken part in the reaction; (4) reactions wherein water combines with other compounds, or is obtained from combinations with other compounds without the water undergoing decomposition, and without the bringing about of any very profound change in the compound wherewith the water combines, or from which the water is withdrawn; and (5) reactions wherein water enters into such intimate chemical union with other compounds that water cannot be obtained again from the products of the reaction without completely breaking up these products; in these reactions, although neither hydrogen nor oxygen is given off, it is likely that a complete rearrangement of the elements of the water and the elements of the other compound takes place.

A short consideration will convince one that many of those reactions which have been asserted to be reactions of water might be described with equal accuracy as reactions of hydrogen; and that many might be described very correctly as reactions of oxygen. For instance, it is surely a reaction of hydrogen that one grain of it combines, under certain conditions, with eight grains of oxygen to produce nine grains of water, and it is a reaction of oxygen that this element combines, under proper conditions, with hydrogen, in the ratio of 8 to 1 by weight, to produce water. Again, the facts that hydrogen is obtained when steam is passed over red hot-iron, and that oxygen is produced when a mixture of steam and chlorine is passed slowly through a very hot tube, might be asserted with perfect accuracy to be reactions of hydrogen and oxygen, respectively, or these same reactions might be claimed to be reactions of iron on the one hand, and of chlorine on the other hand.

It is this manysidedness of the simplest chemical reactions that gives both its great charm and its great difficulty to the study of chemistry. Every reaction must be regarded from several points of view before it can be placed with those reactions that are most like it, and separated from those which do not resemble it. And it must always be remembered that the study of reactions ought to be connected with the study of composition; that the reactions of every definite substance ought to be compared with those of other homogeneous bodies, and that when elements and compounds have been classified on the basis of their reactions further reasons for the classification should be found by tracing similarities between the compositions of those bodies which exhibit similar reactions.

Let us take another instance of the study of reactions to illustrate the methods used, and the kind of results obtained, in this department of chemical inquiry. And this time we shall choose an element—the element hydrogen. The reactions which are first examined when the chemical properties of an element or a compound are being studied are those wherein the body in question is prepared or isolated. Investigation shows that the colourless, odourless, very light gas which is given off when iron is thrown into diluted oil of vitriol is the same gas which is obtained when zinc, or tin, or one of several other metals, is substituted for iron. Then it is found that the same gas can be obtained from water by passing it, in the form of steam, over hot iron, or hot zinc, or hot magnesium, or one of several other metals. Further investigation shows that compounds of the gas in question, from which the gas can be obtained, exist in almost every variety of living things, both animal and vegetable.

These results suggest further inquiries; this gas is obtainable by the interaction of iron, zinc, or several other metals, with diluted oil of vitriol; will the gas be produced if some other acid liquid is substituted for oil of vitriol? Experiments shew that almost anyone of those sour, acrid liquids that are commonly called *acids* may be used instead of oil of vitriol; thus the same gas is produced by the reaction of iron and concentrated vinegar, or iron and spirits of salt, or iron and citric acid dissolved in water, as is produced by the reaction of iron and diluted oil of vitriol. Further suggestions arise from these results. An answer is sought, by experiment, to the question: Is this gas always obtained when iron, or zinc, reacts with an acid? The common acid called *aqua fortis* is tried; and a reddish ga is produced quite different from that obtained when one of the other acids was used.

The reactions between the light colourless gas and other homogeneous bodies are now studied. The gas is found to be inflammable; and water is discovered to be the product of the burning. Accurate quantitative experiments would then be required to find out whether water is the only product, or whether other compounds are produced also. As water is formed when the gas is burnt, the name *hydrogen* (water-producer) is given to the gas. The change that proceeds when hydrogen is burnt to water is then studied in detail and quantitatively; and when the process has been elucidated, the suggestion at once presents itself, that if hydrogen were brought into contact with compounds of oxygen with other elements it would probably rob these compounds of their oxygen and form water. Experiments are tried, and it is found that many compounds of oxygen with the metals are deoxidised when heated in hydrogen, with the production of water, and the metal which was before combined with oxygen. These results, incidentally, suggest a method for obtaining metals from their compounds with oxygen, and this method is found to be applicable in many cases.

Attempts are then made to combine hydrogen with other elements, and results are obtained which suggest an enormous field of inquiry. For instance, hydrogen and chlorine (the badly-smelling gas from common salt) combine easily in the sunshine; the product is a gas which dissolves readily in water, producing thereby an exceedingly acid liquid, which is known in daily life as *spirits of salt*, or sometimes as *muriatic acid* (the name *hydrochloric acid* is more descriptive, suggesting its production from hydrogen and chlorine). Then hydrogen and nitrogen, one of the inert gases in the atmosphere, combine with difficulty under the influence of a succession of electric discharges: but when they have combined they produce a gas with a most penetrating smell, which dissolves very easily in water, producing thereby what is commonly known as *spirits of hartshorn* (because the substance was once made by heating the horns of harts), but is better called *ammonia*. These two compounds, hydrochloric acid and ammonia, both compounds of hydrogen, are examined and compared with other compounds, and they are found to be representatives of two classes of compounds which are much opposed in their chemical characters; to these two classes of compounds are given the names *acids* and *alkalis* respectively. Ammonia is an alkali, hydrochloric acid is an acid.

These results lead to a study of the reactions and the compositions of a number of compounds which, like hydrochloric acid, are sour, which change the hues of various colouring matters, which burn the skin and corrode cotton, wool, wood, and the like; all these compounds are found to be compounds of hydrogen. Attention is turned to the alkalis, potash and soda, slaked lime and baryta, all of which have properties resembling those of ammonia; these compounds are found to be also compounds of hydrogen. Then the chemist naturally inquires what change takes place when I mix an acid and an alkali? He tries, and, after much laborious quantitative work, he finds that a compound is produced which has the properties neither of the acid nor of the alkali; the compound is a mild, neutral substance, unlike the burning acid, and different from the caustic alkali which corroded the flesh so easily. The study of the composition of number of the compounds produced by what is called *neutralising* acids by alkalis shew that in many cases these compounds—which are known as *salts*—do not contain hydrogen, and that if hydrogen is one of the components of a salt, there is always less hydrogen than was contained in the acid from which the salt was produced. What, then, has become of some part, or in certain cases of all, of the hydrogen of the acid? Experiments shew that in almost every case water has been produced when an acid has been neutralised by an alkali to form a salt. Then it is remembered that hydrogen was given off when iron, or zinc, or other metal reacted with certain acids; it is now necessary to find out what becomes of the iron or the other metal which disappears in the acid. The results of a great many quantitative experiments is to prove that the metal combines with the elements of the acid, except the hydrogen, or part of the hydrogen, and that the compound so formed is a salt.

But if both acids and alkalis are compounds of hydrogen, why are some of these compounds so very different in their properties from the others? Acids and alkalis are opposed most markedly in their chemical reactions. Why are acids acidic? Why are alkalis alkaline? To such wide questions as these an examination of the reactions of hydrogen has led us.

The answer given in the older days to such a question as that—Why are acids acidic? was, Acids are acidic because they all contain more or less of the principle of acidity. The form of the answer was sometimes varied a little, and all acids were declared to have in them some portion of the primordial acid. But a *principle of acidity*, and a *primordial acid*, are phrases, neither of which helps to advance accurate knowledge. After seeking for many centuries to express the properties of similar particular kinds of matter by assigning to them all the possession of a common principle, or essence, naturalists have found that nothing comes of this method of classifying, that real knowledge is not advanced by it, that, indeed, when a man has loudly asserted the existence of a principle of acidity in certain bodies, and a principle of alkalinity in others, he is exactly where he was before. The attempts which the chemist makes to find the cause of the acidity of acids and of the alkalinity of alkalis take a different form. The chemist asks—What is the composition of those compounds which have certain reactions in common, and which we call acids? What is the composition of those other compounds we call alkalis, which also have certain common reactions? The only answers chemistry can give to such questions as those we are asking now are answers which shew the connexions between properties and composition. Chemistry ignores the more fine-sounding questions that begin with *Why?* and contents herself with trying to find answers to those that begin with *How?* And the first result of the determination of the compositions of a number of acids is that the acids are all found to be compounds of hydrogen, and that this is the only element which is common to them all. The next question to be answered by experiment evidently is this: Are all compounds of hydrogen acids? A short investigation suffices to answer this question in the negative; it is found, for instance, that alkalis—the antipodes of acids—are compounds of hydrogen. Evidently, then, whether a compound of hydrogen shall or shall not be an acid must be connected with the other elements wherewith the hydrogen is combined. Here is a rich field of research. I cannot tell of the diggings and toilings in this field, of the controversies between rival labourers, of the hopes and disappointments; I must notice only the general result. When hydrogen is combined with a relatively large quantity of one or more oxygen-like elements, of which oxygen itself may or may not be one, the compound is an acid. By "oxygen-like elements" are meant elements which broadly resemble oxygen in their typical chemical reactions; the most common of these elements are chlorine, bromine, iodine, nitrogen, sulphur, and phosphorus. Of course a large amount of accurate study would be required before one could attach a definite meaning to the phrases I have used—"oxygen-like elements," or "elements which broadly resemble oxygen in their typical chemical reactions.' But these phrases present subjects for definite inquiry, they are science-producing expressions; and in this respect they are in complete contrast with such alchemical phrases as *the principle of acidity* or *the primordial acid.*

But which among the various reactions that have been mentioned as belonging to acids is *the* characteristic reaction of acids? Prolonged investigation has enabled chemists to assert that all acids interact in presence of water with metals (the common metals are iron, zinc, copper, mercury, tin, and lead) to exchange the whole or part of their hydrogen for metal, and so to produce salts, that is, compounds of the metal used with the elements of the acid except the hydrogen, or that part of it which has been turned out of the acid by the metal. In other words, either the whole, or some portion, of the hydrogen in certain compounds is more or less readily displaced from these compounds by causing them to interact with metals in the presence of water. Compounds which have this common property are called acids, and these compounds are all formed of hydrogen in union with relatively large quantities of one or more oxygen-like elements. It is then a chemical reaction of hydrogen that, when this element is united with considerable quantities of certain other elements, all of which broadly resemble oxygen in their chemical reactions, the hydrogen leaves its combination with these other elements when an aqueous solution of the compound of which it forms a part interacts with a metal.

What, then, about alkalis? The outcome of very extended experiments is to shew that alkalis are compounds of hydrogen and oxygen with relatively large quantities of elements which in their chemical reactions are the very opposites of oxygen. The hydrogen in alkalis is not turned out by causing them to react with metals.

Summing up, we see that the chemical reactions of hydrogen certainly depend on the kind of elements wherewith the hydrogen is combined. When it is combined with a large quantity of oxygen-like elements it is acidic hydrogen; it can be turned out of these compounds by metals: when it is combined with a large quantity of certain other elements which are chemically very unlike oxygen, then, even although some oxygen also is in these compounds, the hydrogen cannot be turned out by metals; it is chemically quite different from the hydrogen of acids. It is evidently impossible to study the chemical reactions of hydrogen without studying the chemical reactions of many other elements, and many compounds, and the compositions also of many compounds. It is, indeed, literally true that an exhaustive study of the chemical reactions of hydrogen involves an exhaustive study of many chemical reactions of every one of the elements, and of a very large number of compounds also. It may, I think, even be said that a full investigation of any chemical reaction would lead to the investigation of all other chemical reactions; for the reactions of any element or compound are the changes that take place when that body reacts with others to produce certain new substances, and the reactions cannot be regarded as properly investigated when the properties of the new substances only are studied, but the investigation requires the examination of the changes that occur when the new substances react with other substances; and so the study proceeds, until the whole of chemistry is embraced in the scope of the inquiry. And, moreover, the chemical reactions which are known to-day are not so many as those that will be known to-morrow; every day adds new substances, and, therefore, new reactions, to the science. Lack of variety, lack of subjects of inquiry, are impossible in chemistry; the study always draws one on to new fields; it is satisfying, but never gorging; it is difficult, but always fascinating; there is no branch of natural science wherein such a constant demand is made on that accurate and imaginative common sense which is called scientific method.

CHAPTER VI.

CONNEXIONS BETWEEN COMPOSITION AND PROPERTIES.

The brief examination of certain chemical properties of water and of hydrogen which was made in the last chapter necessarily involved the recognition of definite connexions between the chemical reactions and the compositions of the substances examined. But as the study of the connexions between reactions and composition is the very essence of chemistry, it is advisable to devote a chapter to the illustration of the methods employed and of the results obtained.

It is sixty years since Talbot laid the foundations of photography. He dipped paper into a solution of lunar caustic (nitrate of silver), and then brushed over this paper a solution of common salt; on this prepared paper he laid a transparent drawing, and placed the paper and drawing in sunlight; after a little time he removed the drawing, and at once he took the paper, whereon the sun had imprinted a copy of the drawing with the lights and shadows reversed, into a dark room and immersed it in a boiling solution of common salt. Talbot thus obtained a copy of his drawing on which the sunlight was without action; but the lights and shadows of the original drawing were reversed in the copy. He now laid the copy on another piece of paper, prepared by dipping in solution of silver nitrate and brushing over with common salt solution, exposed the arrangement to sunshine, and passed the paper through a boiling solution of salt; and thus he had a copy of the original drawing with the lights and shadows represented as in the original. These processes present an interesting series of changes of properties in certain definite substances. Talbot's process was not quite satisfactory: it was tedious; the first result was apt to fade after being exposed for some time to the light; the copy was not quite so sharp as might be desired, and so on. It was evidently necessary to elucidate, as far as possible, the changes of composition that accompanied the observed changes of properties, and then to compare both series of changes with other changes like them, in order that, reasoning on this basis of well-established facts, remedies might be suggested and modifications might be tried. Now the paper which had been soaked in silver nitrate solution and then brushed over with a solution of salt contained in its pores a deposit of a white solid called chloride of silver. The formation of chloride of silver, by bringing together solutions of silver nitrate and common salt, had been known for a long time before Talbot's day, and the fact was discovered fully two hundred years before Talbot made his experiments that chloride of silver is blackened by sunlight. But what change is brought about in the composition of chloride of silver by the action of the sun? It might well be supposed that a definite answer to this question must be found before photography could make any marked advance; nevertheless it is strange that a definite and undoubtedly correct answer has not yet been given. When chloride of silver is exposed to sunshine there is a very slight decrease in weight, a minute trace of chlorine is removed (chloride of silver is a compound of chlorine and silver), and perhaps an extremely small quantity of oxygen enters into chemical union with portions of the silver and chlorine. Whatever the change of composition may be it affects only a very thin layer on the surface of the chloride of silver.

Talbot found that chloride of silver dissolves in a boiling solution of common salt—a definite compound of silver, sodium, and chlorine is produced—but that the dark-coloured substance produced by the action of sunlight on chloride of silver does not dissolve in this solution. It is inconvenient to work with boiling liquids. After trying various substances, Talbot found that chloride of silver dissolved easily in a cold solution of hyposulphite of soda—a double hyposulphite of silver and soda is produced—and that the product of the darkening of chloride of silver by sunshine was insoluble in this liquid. Here, then, was a distinct step forward. Talbot now tried another compound of silver called iodide of silver in place of the chloride, and he found that a change was brought about by the sunshine in the composition of a minutely thin layer of the iodide of silver, but that this change did not make itself visible until another change was induced by dipping the paper coated with iodide of silver, after exposure to sunshine, into some reagent which reacted with the very small portion of changed iodide of silver to produce a visible image. This was the beginning of new modifications; it was no longer necessary to expose the sensitive paper to the action of sunlight until a picture was imprinted on it visibly, but a very short exposure sufficed so to change a minute quantity of the sensitive salt that another change was brought about by the reaction of some other reagent on this altered trace of the sensitive salt, and a visible picture was the final result. Those reagents which act on chloride or iodide of silver, and also on bromide of silver, after exposure of these salts of silver to sunlight, are called *developers*, for they develop the picture by causing changes in composition and properties in those portions of the salts of silver that have already been changed, although only to an extremely small extent, by the action of sunlight.

The process of producing pictures of objects by concentrating the rays of light coming from those objects on to one spot, by means of lenses, was introduced by Daguerre, following the lines of Niépce, towards the end of the thirties of this century. Since that time lenses and cameras have been very greatly improved, but the principles of this, the physical, part of photography remain unchanged.

The sensitive surface on which the picture of an object is to be drawn by the sun is generally prepared nowadays by dissolving bromide of potassium, or bromide of ammonium, in water, adding gelatin, and then an exactly sufficient quantity of silver nitrate solution to react with the whole of the bromide of potassium, so as to produce solid silver bromide, and potassium nitrate which remains in solution; an emulsion is formed by shaking until the solid bromide of silver is disseminated, in extremely small particles, through the gelatin solution. This emulsion is then heated for a time—these operations are, of course, carried on in the dark, or in a room lighted by orange-red light—and allowed to cool, and the semi-solid gelatin, with the minute particles of silver bromide disseminated through it, is washed with cold water until everything that will dissolve in water has been removeed. The washed gelatin emulsion is thoroughly mixed with enough gelatin solution to make it the proper consistency; and this semi-liquid emulsion is poured evenly over clean glass plates, which are then allowed to dry. When a prepared plate is exposed in the camera for a fraction of a second to the rays of light which come from an object outside the camera and are collected and concentrated on the plate by the lenses, a change of composition, accompanied by a change of properties, is brought about in an extremely thin film on the surface of the bromide of silver on the plate. The change of composition is certainly one wherein a minute trace of bromine is removed from silver bromide; and it is probable, but not certain, that a compound, or compounds, of silver, bromine, and oxygen (from the air) is formed The trace of bromine removed from the silver bromide that has been affected by the rays of light is absorbed by the gelatin, wherein it produces one or more compounds. The amount of change on the sensitive surface of the plate depends on the intensity of the light that falls on it, more light comes from the lighter parts than from the darker parts of the objects; and, therefore, the amount of chemical change is greatest in those parts of the silver bromide on which the rays from the more lighted portions of the objects have impinged.

At this stage nothing is to be seen on the plate; the picture must now be developed For this purpose the plate is immersed in a solution of some reagent which removes bromine, and perhaps oxygen also, from the compound (or compounds) that have been formed by the action of light on the silver bromide, and by doing this produces silver in a state of very fine division. The action of the developer generally used seems to extend beyond the minute quantity of photochemically changed silver bromide; these developers probably remove bromine, and hence produce silver, from some of the silver bromide which has not been changed by light. As the process of development proceeds a picture of the objects appears, with the lights and shadows inverted, the picture being built up of very finely divided black particles of silver. As most light has reached the plate from those parts of the objects which were most highly lighted, it follows that the decomposition of the silver bromide has been carried furthest in those parts of the plate, and that the deposit of silver, produced by the developer, is thickest on those parts; that is to say, the highest lights of the objects produce the darkest picture on the plate. When the developing process is finished the unchanged silver bromide is dissolved off the plate by immersing the plate in a solution of hyposulphite of soda, and then washing very thoroughly in running water; the picture is now said to be *fixed*.

I need not go into the processes whereby the picture on the plate is reproduced on sensitised paper with the lights and shadows in the same order of brilliancy as they were in the original objects. Suffice it to say that the plate is covered with a piece of paper which is coated with a silver salt (generally silver chloride), and light is allowed to fall through the plate on to the sensitised paper, wherein changes are brought about more or less similar to those which occurred on the plate when it was exposed in the camera. The light reduces the silver salts in the paper, and the compounds thus produced are reddish-brown; reduction occurs to the least extent on those parts of the paper which are covered with the thickest silver films on the plate, so that those parts of the original objects which were most lighted appear also most lighted in the final print. The print is now *toned* by immersion in a solution of chloride of gold; the various compounds which form the picture on the print break up this gold salt, and a small quantity of gold is deposited on the picture; the object of this process is to impart a pleasing colour to the print. The silver chloride which remains in the paper unchanged is now removed by immersing the paper in a solution of hyposulphite of soda; the paper is then thoroughly washed and allowed to dry.

Parts of the processes used in photography are certainly physical, and part of the success depends on using skilfully made instruments; but the changes whereon the essential portions of photographic processes rest are changes in the compositions and properties of definite chemical compounds. The change, the almost infinitely minute but still definite change, brought about by the light in the sensitive silver bromide produces a compound (or compounds) whose most marked property is its power of reacting, gradually, with other definite compounds, that are called developers, to produce silver. Then there is the fact that silver bromide reacts with hyposulphite of soda to form a compound which is soluble in water, whereas no action occurs between hyposulphite of soda and either silver or the compound (or compounds) formed by the action of light on silver bromide. This gradual development of the wonderful art of photography is a striking instance of what may be done by studying the connexions between definite changes of composition and definite changes of properties. It is true that many improvements have been made in photographic processes by people who neither knew nor cared much about the exact study of material changes; but it is also true that all the deep-seated changes in the art, all the far-reaching discoveries, have come from accurate and painstaking attempts to find out what changes in composition actually take place during the different parts of photographic processes, and in what ways these are connected with changes of properties.

The next example I give of the results of the study of the connexions between changes of composition and changes of properties will be taken from the manufacturing industries. There are great differences between the properties of iron and those of ironstone; the properties of the former make it the most useful of the metals, whereas ironstone is of no use in itself, but only in that it is a source of iron. Corresponding with these differences in properties, there must be some difference in composition; if the latter difference is known it will doubtless be possible to arrange reactions whereby the passage from the one substance to the other may be accomplished. Analyses of ironstones shew that most of them contain compounds of iron and oxygen, mixed with other compounds of other elements. The problem then is to remove oxygen from its combination with iron. Now it is known that charcoal or coke burns fairly easily, and that while burning it combines with oxygen; moreover, experiments in the laboratory shew that when a mixture of finely powdered charcoal and oxide of lead, or oxide of copper, is heated, the glowing charcoal takes oxygen away from the metallic oxide, and produces carbonic acid gas and lead, or copper. Further experiments on the burning of charcoal, or coke, shew that when a layer of one of these materials is lighted at the bottom, and is fed with sufficient air from beneath, the carbonic acid gas which is produced is deprived of half its oxygen as it passes through the upper layers of heated charcoal, or coke, and a gas is produced which is called carbon monoxide. This carbon monoxide is easily inflammable in the air; it burns with a pale blue flame and produces carbonic acid gas; it also easily removes oxygen from various metallic oxides when heated with them

Here, then, are chemical reactions on which may be reared a process for converting ironstone into iron. If the ironstone is mixed with charcoal, or coke, and strongly heated, air being admitted from beneath, some of the charcoal, or coke, will be burnt to carbonic acid by the oxygen which is admitted in the air, but some of it will probably be burnt by oxygen which it withdraws from the oxide of iron in the ironstone. Moreover, as the carbonic acid gas passes upwards it will most likely be robbed of half its oxygen by the hot charcoal, or coke, through which it passes; and if this happens, a gas– carbon monoxide– will be formed which is eager to combine with oxygen wherever it can get it, and which will, therefore, in all likelihood, take away oxygen from the oxide of iron in the ironstone. By two different reactions, then, will the wished-for change be accomplished; oxygen will be taken away from the oxide of iron by the reaction between that oxide and charcoal, or coke, at a high temperature, and oxygen will be removed from the same oxide of iron by the reaction between it and the carbon monoxide which is produced by burning the charcoal, or coke, under special conditions.

These two reactions are those which take place, along with other chemical changes, in the blast furnaces where ironstone is changed into iron.

The reactions which occur between oxides of metals and carbon at high temperatures have been turned to account in the preparation of many other metals besides iron from their ores. Many metallic ores contain compounds of the metals with oxygen; many others contain compounds with sulphur; and some, called carbonates, contain compounds with carbon and oxygen. Now, as almost all metallic sulphides can be converted into oxides by roasting in a current of air—the sulphur is burnt off, being changed to gaseous sulphur dioxide, and oxygen from the air combines with the metal that is freed from sulphur and as most, if not all, metallic carbonates can be changed into oxides, and carbonic acid which goes off as gas, by heating strongly, it is evidently no difficult task to convert the sulphide, or carbonate, of a metal in an ore of that metal into the oxide. And when the oxide has been obtained, the metal itself can very frequently be produced by strongly heating, in a suitable apparatus, a mixture of the oxide with charcoal or coke.

An examination of the change of composition that accompanies the change of properties when a naturally occurring metallic ore is converted into a metal, has enabled the processes which are likely to prove effective in the extraction of this or that particular metal from its ores to be arranged together, so that one who has a general, and at the same time accurate, knowledge of this class of reactions knows which processes are worth trying should he have to deal with some new problem in the isolation of a metal from those compounds of it that are found native. And more than this, a knowledge of the kind I have spoken of enables a man to suggest new methods when all the ordinary and commonly used methods have failed. He knows the general character of the only methods he need attempt; he cuts out a great many processes which the mere rule-of-thumb man might be likely to waste time and energy in trying; he goes at once to the root of the matter.

Take, for instance, the preparation of aluminium, a metal which has come into considerable use within the last few years. Compounds of the oxide of aluminium with silica occur in very large quantities in the earth; these compounds form the clays. Judging from the reactions that occur when many metallic oxides are heated with charcoal, it seemed possible that aluminium might be obtained by heating a mixture of the oxide of that metal—obtainable from clay without much difficulty—and charcoal. But when this reaction was tried, the oxide of aluminium was not deprived of its oxygen. The compounds which metals form with chlorine, bromine, or fluorine always shew distinct analogies in their chemical reactions with the metallic oxides. As oxygen can very often be torn away from a metallic oxide by heating that oxide with carbon, or in a stream of gaseous carbon monoxide, or with the extremely poisonous compound called potassium cyanide, so chlorine, bromine, or fluorine can generally be removed from a metallic chloride, bromide, or fluoride by the reaction of the metal sodium, or the metal zinc, with the melted chloride, bromide, or iodide. These reactions were applied, and applied successfully, to the isolation of aluminium. Aluminium chloride, or, rather, a compound of aluminium and sodium chlorides, was prepared from clay; this compound was melted, and pieces of the metal sodium were pressed into the semi-liquid mass; an exceedingly violent reaction occurred; common salt was formed by the union of the sodium with the chlorine which was torn away from its combination with aluminium; and the melted aluminium, now removed from its union with chlorine, was poured out into iron moulds.

But this method for making aluminium was not commercially successful, the preparation of the compound of aluminium and sodium chlorides from clay was a tedious and somewhat difficult business, and the preparation of the metal sodium was expensive. Now it was known that many chlorides, bromides, or fluorides of metals are torn asunder into their constituents when these salts are melted and a current of electricity is sent through the melted salts. This method was tried with aluminium fluoride, and was successful. A compound of aluminium fluoride with sodium fluoride occurs native, it is called *cryolite*. All that need be done to get aluminium from cryolite is to mix the mineral with a certain amount of common salt—the mixture melts more easily than cryolite alone—to melt this mixture, and to pass a current of electricity through the molten substance.

Turn back for a moment to the iron made by removing oxygen from ironstone. Iron made in that way is not pure iron; it contains several *per cents.* of carbon, which makes the iron fusible and capable of being run into moulds, or *pigs* as they are called in the iron trade. Steel is *nearly* pure iron; at least, it is iron containing considerably less carbon than pig iron. As steel is much harder than pig-iron, and as it can be tempered, a process which pig-iron refuses to undergo, it is an exceedingly useful variety of iron. How, then, can pig iron be changed into steel ? The problem is to remove from pig-iron somewhat more than half the quantity of carbon it contains, but to leave about 1 to 1½ *per cent.* of carbon in the product.

If air is blown into melted pig-iron, the whole of the carbon is burnt to carbonic acid, and at the same time a little of the iron is burnt to iron rust (iron oxide). It is not possible to stop the burning process at the point whereat just enough carbon has been burnt to insure the formation of steel; but it is possible to stop the process exactly when the last trace of carbon has been burnt away; and it is then easy to stop the inrush of air, and to add exactly enough carbon to convert the contents of the vessel into steel. The *Bessemer process* for making steel takes advantage of the different behaviours of iron and carbon towards air at a high temperature. Huge pear-shaped vessels, made of plates of wrought iron and lined with fireclay, are employed; several tubes pass through the bottoms of the vessels, and air can be blown in through these tubes. The vessel is charged with molten pig-iron; air is blown in, and at once the burning processes begin. The carbon is burnt rapidly to carbonic acid, which escapes as gas, and at the same time a little iron is converted into oxide. When the last trace of carbon is burnt away—the exact point is indicated by a sudden change in the appearance of the flame issuing from the vessel—the air blast is stopped; enough carbon is added to convert the almost pure iron in the vessel into steel (of course, the weight of material in the vessel is known), and the molten contents are run into proper vessels wherein the steel cools. The small quantity of iron oxide produced in the burning process remains unmelted as a dross or cinder which does not mix with the molten steel.

These cases—the art of photography, the production of iron from iron ore, and steel from iron, and the production of aluminium from compounds of that metal which are found in the earth– are illustrations of the results that have been obtained by the careful study of the connexions between changes of properties and changes of composition, that is, by the study of chemical transformations. The illustrations have been taken from the sphere of technical chemistry. I should now like to give some examples both of the results, and of the methods used, of a more general character than any that can be selected from those chemical transformations, all more or less special, which are turned to account in so many manufacturing industries.

Oxygen combines with every one of the elements except bromine and fluorine, these compounds, each of oxygen and one other element, are called *oxides*. Here, then, is a large number of compounds with a similar composition; they are all binary compounds of oxygen. The study of the chemical reactions of this class of compounds, related so definitely in their composition, cannot but be of interest. Some oxides dissolve easily in water, others dissolve with difficulty, and some do not dissolve at all. Aqueous solutions of certain oxides are acrid, corrosive, and biting; they dissolve many metals with the evolution of a gas which is often hydrogen, and they dissolve washing soda, or chalk, giving off carbonic acid gas. Aqueous solutions of certain other oxides have a soap-like feel, but are not acrid nor biting; these solutions do not dissolve metals, washing soda, or chalk, with evolution of gas. When definite quantities of a pair of oxides, one belonging to the first, and the other to the second, of these classes, are mixed in aqueous solutions, the characteristic properties of both oxides vanish; a liquid is obtained which is neither acrid nor corrosive, nor soapy to the touch; this liquid does not dissolve metals, nor chalk, nor washing-soda with evolution of a gas. The prominent properties of the liquid are best described by the word *neutral*. When this neutral liquid is evaporated, and then allowed to cool, a solid separates, generally in crystals, and an analysis of this solid shews that it is composed of the two oxides aqueous solutions of which were mixed. The two oxides have combined to form a definite substance whose properties are different from those of either of the oxides; the characteristic properties of the oxides have been lost in the properties of the new substance.

It is customary to call those oxides which dissolve in water to form acrid liquids, that dissolve metals, *acidic oxides*; and to give the name *basic oxides* to those whose aqueous solutions are not acrid and do not dissolve metals. The compound that is formed by mixing definite quantities of aqueous solutions of two oxides, one of which is acidic and the other basic, and evaporating, is called a *salt*. It is found that many oxides which do not dissolve in water nevertheless dissolve in aqueous solutions of acidic oxides, combining with these acidic oxides to form salts; oxides which react in this way are included among the basic oxides. Again, there are several oxides which do not dissolve in water, but which combine with basic oxides to form salts when heated with them; such oxides are included among the acidic oxides. In all these reactions, of course, definite quantities of the various oxides react, and the weight of each oxide which takes part in any one of the reactions is always expressible as a whole multiple of the reacting weight of that oxide (*see back*, p. 66); moreover, the total weight of all the products of each reaction is exactly equal to the total weight of all the definite bodies that have reacted.

There are some oxides which do not belong to either of those divisions we are considering; but the two classes of acidic and basic oxides contain more than three-fourths of all the oxides.

Let me illustrate the reactions of basic and acidic oxides by describing three cases in a little detail. When carbon is burnt in plenty of oxygen, or of air, the carbon gradually disappears, if the burning is carried on in a jar, and if some water is poured into the jar when the burning is done, and the jar is shaken, the water is found to have become sour to the taste, it is able to change the hues of various colouring matters, and to dissolve some metals (not by any means all metals) slowly with evolution of hydrogen. Carbonic acid gas has been produced and has dissolved in the water If a solution in water of a little of another oxide, namely, oxide of sodium, is prepared, that solution has the properties already enumerated as being characteristic of basic oxides, the liquid is, indeed, weak soda lye. Carbonic acid gas can also be made by pouring hydrochloric acid on to lumps of marble; if the gas is passed into an aqueous solution of the basic oxide of sodium until the bubbles of the gas cease to be absorbed by the liquid, and if the liquid is then evaporated considerably and allowed to cool, a white crystalline powder separates, and this powder is proved by quantitative experiments to be bicarbonate of soda. The salt bicarbonate of soda has been produced by the interaction of definite quantities of carbonic acid gas, which is an acidic oxide, and sodium oxide, which is a basic oxide.

A liquid having all the properties, to a very marked degree, of solutions of acidic oxides is obtained by dissolving a certain white crystalline compound called sulphur trioxide in water. The liquid is very sour, very acrid and corrosive, it burns holes in one's clothes, it irritates the flesh, it dissolves many metals, even without heating, and it rapidly evolves carbonic acid gas from washing-soda or chalk. If some of this liquid is heated, and iron rust, which is composed of iron and oxygen, is thrown into the hot liquid, the rust gradually dissolves; if the addition of rust is continued till a little of it refuses to dissolve, if the liquid is then strained off through a filter from the undissolved rust, evaporated until it is nearly dry, and allowed to cool, a pale yellowish brown solid is obtained which shews none of the characteristic reactions of either oxide by the reaction of which it has been produced. Quantitative analyses prove that this solid is composed of ferric oxide (rust) and sulphur trioxide, and its reactions cause it to be placed in the class of salts.

There is a yellow salt called chromate of potash, which is largely used as a colouring material, and from which many other colouring materials are obtained. This salt is a compound of the acidic red oxide of chromium and the basic oxide of potassium. The commonest mineral which contains compounds of chromium is *chrome-ironstone*, the main constituents whereof are oxide of iron and an oxide of chromium called the green oxide; this oxide of chromium is basic, it contains less oxygen, relatively to a fixed weight of chromium, than the red, acidic, oxide. One result of a long series of examinations is that although the red, acidic, oxide of chromium cannot be prepared by directly adding oxygen to the green, basic, oxide, nevertheless if the green oxide is heated for a long time in the air in the presence of solid oxide of potassium (solid potash, which is composed of potassium, hydrogen, and oxygen, is used), and of a flux which serves to keep the whole mass melted, the green oxide combines with oxygen which it takes out of the air and forms the red, acidic, oxide, and simultaneously the red oxide of chromium combines with the basic oxide of potassium that is present, and the wished for salt, chromate of potash, is produced. The process cannot be stopped at the half-way house marked by the formation of the red, acidic, oxide of chromium; but this does not matter, as the object of the manufacturer is, not to isolate this oxide, but to apply the typical reaction which occurs between an acidic and a basic oxide to this oxide and the basic oxide of potassium.

The study of the reactions of oxides, that large class of compounds which are so far like one another in composition that each is composed of oxygen and another element, has led to the division of the greater number of the oxides into two classes, *acidic oxides* and *basic oxides*. Even a cursory examination of the reactions of these two classes of oxides has carried us away from oxides to another class of compounds called *salts*. And in our attempts to elucidate the reactions of those compounds of oxygen, the oxides, we have reached results which had already been obtained in our attempts to elucidate the reactions of certain compounds of hydrogen. In studying the connexions between the compositions and properties of a great class of compounds of hydrogen, the acids, we found that a salt is always one of the products of the reaction between an aqueous solution of an acid and a metal. We now know that a salt is also produced when an aqueous solution of an acidic oxide interacts with a basic oxide. This, of course, obliges an inquiry to be made into the compositions of those oxides that are basic; the result is, as might have been expected, that basic oxides are oxides of metals, that is, of elements which resemble iron, copper, lead, tin, silver, and gold (compare what was said about metals in the last chapter, p. 88).

But what kinds of elements are those whose oxides are acidic? The answer given by experiment is most acidic oxides are oxides of elements which are chemically and physically unlike the metals, and which elements chemically resemble sulphur, phosphorus, nitrogen, and oxygen. We have already (p. 87) called these elements oxygen-like elements; they are more commonly classed together under the name *non-metals*.

Two questions remain, directly suggested by the results we have obtained, and a comparison of these with those which the study of hydrogen taught us regarding acids and salts. A metal interacts with an acid to form a salt, and a gas which is generally hydrogen; the salt is composed of the metal and the elements of the acid save the hydrogen, or a portion of the hydrogen, (see p. 85); but a basic oxide, which is an oxide of a metal, reacts with an aqueous solution of an acidic oxide to form a salt without the evolution of hydrogen or any other gas. Does an aqueous solution of an acidic oxide then contain an acid? And when a basic and an acidic oxide react in solution is anything formed besides the salt, and if so, what is formed? These questions open a very great field of inquiry, which cannot be gone into here. Suffice it to say that an acid is formed in almost every case when an acidic oxide dissolves in water; the solution is accompanied by an interaction between the oxide and the water; and the product of this interaction is an acid, which is a compound of hydrogen (from the water), oxygen, and the non-metallic element the acidic oxide whereof was dissolved in the water. And the most probable explanation of the changes of composition that occur when an aqueous solution of an acidic oxide—that is, an aqueous solution of an acid—interacts with a basic oxide, is to the effect that the metal of the basic oxide turns out the hydrogen, or a portion of the hydrogen, of the acid, and, combining with the other elements that formed the acid, produces a salt, while the hydrogen that was removed from its combination enters into union with the oxygen of the basic oxide and forms water.

One general result of the very cursory examination we have been able to make of the reactions of oxides is that the chemical properties of these compounds depend, in some measure, on the general chemical character of the elements that are combined with oxygen. This result is exactly similar to that we arrived at from the study of certain compounds of hydrogen; for we found that the chemical properties of hydrogen depend (there may, of course, be other conditioning circumstances) upon the general chemical character of the elements, and also upon the relative quantities of the elements, wherewith the hydrogen is combined (compare p. 89). Perhaps the relative quantities of oxygen combined with another element may affect the basic or acidic reactions of the oxides of that element. Experiments shew that the basic or acidic characters of oxides are undoubtedly conditioned by the relative quantities of oxygen they contain. To give only two examples. There is an oxide of the metal manganese which contains weights of manganese and oxygen combined in the ratio (expressed in round numbers) of 1 to $\frac{1}{3}$, and that oxide is decidedly basic; there is another oxide of the same metal which is distinctly acidic, and that oxide contains weights of manganese and oxygen combined in the ratio (using round numbers) of 1 : 1. There are two oxides of chromium, one of which contains just twice as much oxygen as the other combined with the same weight of the metal; that oxide with the smaller quantity of oxygen is basic, and that with the larger quantity of oxygen is acidic.

The study of the reactions of oxides leads to the study of acids, salts, metals, and non metals. This study illustrates what I said before that every chemical interaction contains in itself the whole science of chemistry. I have tried in this chapter to indicate the nature of the problems the chemist has to deal with, to outline some of the methods he uses in trying to solve these problems, and to notice a few of the results he has obtained. I would conclude the chapter by insisting on the fact that the study of the connexions between composition and reactions, and as a necessary consequence the examination of the connexions between changes of composition and changes of reactions is the very essence of chemistry. To examine a thing as it is, apart from other things, is not the business of the chemist. When change begins chemistry begins. And as *the* feature of human life is variability, and as nine-tenths of our manufactures are concerned with changes in material things, chemistry is the science which enters most intimately into the daily life of humanity.

CHAPTER VII.

THE COMPOSITIONS AND PROPERTIES OF SOME COMPOUNDS OF CARBON.

There is one element the number of whose compounds is greater than the sum of all the compounds of all the other elements; that element is carbon. Diamond is almost pure carbon; charcoal, graphite, lampblack, coal, and coke are mixtures of carbon with various other substances. The flesh, blood, bones, tissues, and all the other parts of animals contain large quantities of compounds of carbon; and compounds of this element form the greater part of every plant. Vast quantities of carbon compounds are found in the crust of the earth; about 3 lbs. of every 10,000 lbs. of air consist of a compound of carbon; and the same gaseous compound is found dissolved in almost every specimen of water. And besides the great array of compounds of this element that is distributed through nature, many thousands of other compounds of the same element have been prepared in the laboratory.

The range of properties of the compounds of carbon is very great. Some are solids, some liquids, and some gases, under ordinary conditions of temperature and pressure; and the colours and appearances of these compounds are as varied as their number is large. All the aniline dyes are compounds of carbon; guncotton, nitro-glycerin, and the constituent compounds of all smokeless powders are compounds of carbon; alizarin, indigo, and the colouring compounds of saffron, brazil-wood, logwood, and cochineal belong to this class; all ordinary kinds of fuel—coal, wood, peat, coal-gas, and oils—are mixtures of compounds of carbon; almost every kind of food we consume is a mixture of compounds of this element; the characteristic constituents of almost all our beverages are carbon compounds; the greater number of the drugs that are used in illness are mixtures of this class of compounds; all, or almost all, the evil-smelling gases that are produced when animal or vegetable matter decays are compounds of carbon; and all the odours of sweet essences, and the delicate bouquets of choice wines are the odours and the bouquets of compounds of the same element—carbon. The chemical reactions of these compounds are surprisingly numerous and surprisingly different: some compounds are oxides, many are acids, and many are salts; and there are also representatives of dozens of classes of compounds which are not to be found among the compounds of any of the other elements. The study of the compounds of carbon is eminently fitted to throw light on the central problem of chemistry, the problem, that is to say, of the connexions between composition and reactions.

Suppose a person with some general knowledge of chemical changes—let us say, one of those who have followed the course of this book to the present chapter—had put before him a statement of the qualitative composition of each one of the compounds of carbon known to-day, I am certain his first remark would be: "How vast a number of different compounds is formed by the union of so small a number of different elements." For the statement would reveal the fact that by far the greater number of the compounds of carbon —I suppose there would be at least 20,000 of them—are compounds of that element with the three other elements hydrogen, oxygen, and nitrogen, or with two of these three elements. The statement would include a very fair number of compounds containing chlorine, or bromine, or iodine, or sulphur, in addition to carbon and one or more of the three elements just mentioned; and there would be a tolerable show of compounds containing metals, besides carbon, and hydrogen, oxygen, and nitrogen, or two of these three elements. Nevertheless the great bulk of this array of compounds would be found to be compounds of carbon with two, or at most with three, other elements. We have evidently rich material in the compounds of carbon for studying the connexions between composition and reactions.

Although there is such a great number of carbon compounds, and although the reactions of them differ much, yet the classification of these compounds on the basis of reactions is more definite, descriptive, and suggestive than the classification of the comparatively small number of compounds of the other elements.

Each of these many compounds has its own perfectly definite and quite unchangeable composition. The weights of the elements united in any one of the compounds are expressible by the combining weights, or by whole multiples (not generally very large whole multiples) of the combining weights, of the elements in question. Take, for instance, compounds of the four elements carbon, hydrogen, oxygen, and nitrogen. The symbol for the first of these elements is C, for the second H, for the third O, and for the fourth N; and each of these symbols represents one combining weight of the element symbolised (the values of the four combining weights, in round numbers, are C = 12, H = 1, O = 16, N = 14). The compositions of all the compounds which have been formed, or which can be formed, by the union of these four elements is expressed by the single formula

$$C_a H_b O_c N_d;$$

where a, b, c, and d are whole numbers. If any values not greater than 10 were given to each of the indices a, b, c, and d, the symbols would express the compositions of a large number (but by no means all) of the compounds that have been isolated of carbon with the three other elements.

Each of the many compounds of carbon has its own peculiar reactions which mark it off from every other definite kind of matter; nevertheless, the reactions of many of the compounds are so much alike that these compounds may be put together in one class; the reactions of another considerable number are so similar that these are put into another class; and so on.

All I can do is to trace in merest outline some of the results obtained by the study of the twofold aspect of a few compounds of carbon. I shall try to state the results so as to suggest the methods by which they have been attained.

For the purpose of gathering together the compounds of carbon under a common name, it is customary to speak of them as *organic compounds*. But these two expressions, organic compounds and compounds of carbon, have not always had the same meaning. Many of the compounds known to the earlier chemists were obtained from substances of animal or vegetable origin; these compounds, coming from organic sources, were naturally called organic compounds. As it was deemed very important about a century ago to emphasise every distinction between living and non-living things, chemists used to assert that the elements of which organic compounds were composed must be different from the elements that build up the compounds contained in minerals. But analyses of organic compounds were amassed; these compounds were found to be composed of elements well known to the student of mineral chemistry. Then it was said that the arrangement of the elements in organic compounds must be different from the arrangement of the elements in inorganic compounds, that is, compounds obtained from inorganic sources. If one asked; Why must there be some essential difference between organic and inorganic compounds? one was told that organic compounds were built up in the plant or the animal by the agency of "vital force," an agency unknown in the inorganic world; and that where "vital force" came in it produced results radically unlike those brought about by any other cause.

The controversy, kept aflame, like so many others, by giving different, and always indefinite, meanings to the same terms, was stilled and then extinguished by the results of a series of experiments published in 1828 by a great German chemist named Wohler. If there be any compound which is a typical product of the working of living organisms that compound is *urea*. In 1828 Wöhler prepared urea from compounds of mineral origin; that is, in the language of the "vital force" school, Wohler prepared, without the aid of "vital force," a compound which till then had been prepared only by the action of "vital force." Many other compounds regarded as distinctive products of the action of the "vital force" were prepared soon afterwards from inorganic sources; and when twenty or thirty years had passed "vital force" had disappeared from the domain of chemistry.

Organic chemistry has then to aim at the expression of the connexions between the properties and the compositions of compounds of carbon in general statements, which shall hold good in all particular cases, and which shall shew forth the essential characteristics of the relations that have been ascertained. Organic chemistry has advanced some way towards this goal, but she is yet far from the end of the journey.

Among the earliest, the most indefatigable, and the most daring, workers in organic chemistry are to be mentioned Liebig and Dumas, two great men of science whose names are ever to be held in renown by all students of nature. In 1867 Liebig was asked by Dumas why he had ceased to work at the chemistry of carbon compounds;

Liebig replied that "with the theory of substitution as a foundation, the edifice may now be built by workmen; masters are no longer needed." In the opinion of one of the great masters of the science, the theory of substitution was the foundation of organic chemistry.

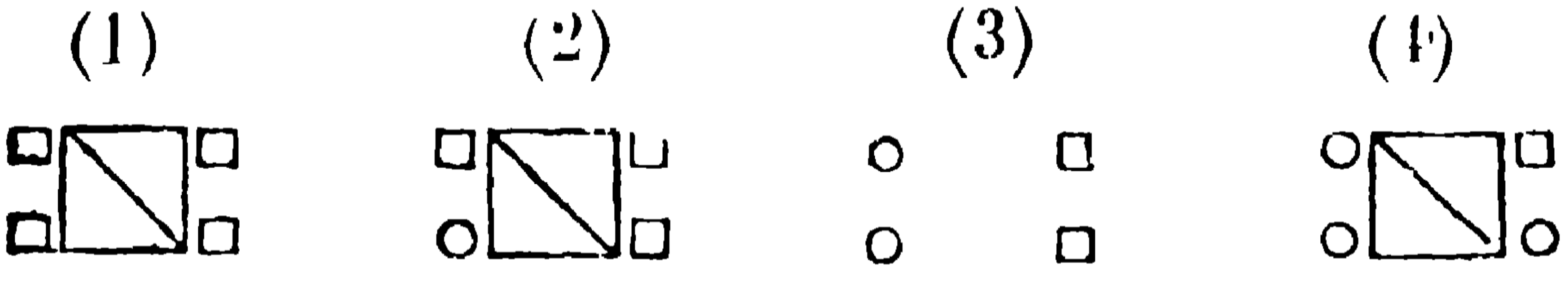
The conception of *substitution* must, then, be one of the most important main results of the study of organic chemistry. Let us try to understand what this conception is.

The mental picture corresponding to the word *substitution*, as that word is used in organic chemistry, is a complex one. In the words I have quoted, Liebig likened substitution to the foundation whereon the edifice of organic chemistry was to be built. It is essentially a builder's image; we shall best understand it by thinking of some series of organic compounds as buildings.

During one of the royal *soirées* at the Tuileries, when Charles X. was King of France, the wax candles used to light the rooms gave off irritating vapours which annoyed the visitors. Dumas was summoned and requested to find the reason, and the cure, for the trouble. How had the wax been made so white? asked Dumas. By bleaching it. What was the bleaching agent? Chlorine. Wax, Dumas knew to be a mixture of compounds of carbon, hydrogen, and oxygen, hydrogen combines easily with chlorine to form the extremely irritating gas, hydrochloric acid. Here was a possible cause of the fumes which came from the candles. If some of the chlorine used for bleaching the wax were retained in the wax, then the heat produced by the burning candles might well cause chemical changes to proceed and hydrochloric acid gas to be given off. Dumas found that the fumes which annoyed the guests at the Tuileries contained hydrochloric acid; and he found that this was produced by changes in compounds of carbon, hydrogen, and chlorine formed in the wax during the bleaching of it by chlorine. The cause and the cure were found. The wax must no longer be bleached by chlorine, because if chlorine is used some of it will always enter into chemical union with compounds in the wax, and when a candle made of this wax is lighted other chemical reactions, wherein hydrochloric acid gas is produced, will occur.

But Dumas was not content to stop here. He investigated the reactions that take place when chlorine is passed over wax; and from that he passed to the examination of interactions between chlorine and various organic compounds. He found that in many of these reactions hydrogen was removed from the compound used, and chlorine entered into union with the elements which remained, producing in this way a new compound whose general chemical reactions were very often extremely like those of the original compound. Take, for example, some of the results of Dumas' investigation of the reactions between chlorine and *acetic acid* (the acid of vinegar), an acid composed of carbon, hydrogen, and oxygen. Dumas found that the reactions proceeded in three stages, and that the products of each stage were a new acid, resembling acetic acid in its general chemical behaviour, and hydrochloric acid gas. He found that each of the new acids was composed of all the carbon, all the oxygen, and a portion of the hydrogen, of the acetic acid, combined with a definite weight of chlorine. And he found that the relations between the weights of the hydrogen in the parent acid, the hydrogen removed from that acid in each stage of the reaction, and the chlorine which entered into combination with the carbon, oxygen, and hydrogen that remained, could be most simply expressed by saying that, in each stage one-fourth of the total hydrogen in the acetic acid was taken away, and chlorine was put in place of it, in the proportion of 35·5 parts by weight of chlorine for one part by weight of hydrogen removed.

Dumas' results may be pictured crudely in the following diagrams.



These diagrams represent the compositions of acetic acid and the three acids obtained by the reactions of chlorine with it; in each, the symbol ⧅ is meant to represent the sum of the weights of carbon and oxygen in the reacting weight of one of the acids; this symbol is unchanged throughout. The small squares represent combining weights of hydrogen, and the small circles stand for combining weights of chlorine, a combining weight of chlorine being 35·5 times heavier than a combining weight of hydrogen.

The compositions of the four acids are represented in ordinary chemical formulæ as follows: -

$C_2H_4O_2$ acetic acid.

(1) $C_2H_3ClO_2$; (2) $C_2H_2Cl_2O_2$; (3) $C_2HCl_3O_2$

(1), (2), and (3) are the new acids produced from the parent acetic acid.

In these reactions Dumas said he had *substituted* chlorine for hydrogen without destroying the general chemical character of the acetic acid. The three new acids were proved by him to be very like acetic acid in their chemical behaviours; he called them *monochloracetic*, *dichloracetic*, and *trichloracetic acid*, respectively. These four compounds, said Dumas, belong to the same type or class. The removal of a definite weight of hydrogen, and the simultaneous substitution for it of a definite weight of chlorine, has not been accompanied by a falling to pieces of the whole building. This process of substitution is like that of removing two or three wooden beams, or it may be a number of stones, from a house, and replacing them by a single beam of iron; the house does not fall to pieces if the operation is done with care. But as there are limits beyond which the substitution of one kind of material for another cannot be carried in a building without imminent risk of collapse, so chemical substitution cannot be repeated indefinitely. In the case we are considering there seems room for one other repetition of the process. The last of the three acids still contains hydrogen (see the diagrams, p. 122, or the formulae, p. 123); cannot this, too, be taken away and a compensating weight of chlorine be put in its place? Experiments shew that if the reaction with chlorine is pushed further than the third stage, by raising the temperature, new compounds are produced which are totally unlike acetic acid; that, in other words, there is a general breaking up of the whole building.

In a process of substitution, an element, or a group of elements, is taken out of a compound, a part of a chemical building is removed, and another element, or group of elements, is put into the vacant place, another kind of building material is put into the building in the place of that which was removed. The new compound is not the same as the original compound, the new building differs somewhat from the old building; but both compounds are much alike, both buildings are of the same class or type. As the removal of some wooden supports, with perhaps a couple of cartloads of bricks and rubble, from above the windows of a shop, and the substitution of a single iron beam in the place of the material removed, and a single large window for the several smaller windows taken away, improves the shop, but does not change it into something which is not a shop, so the process of substituting one element for another, or one group of elements for another, does not necessarily destroy the general chemical character of the compound that undergoes the process, for the compound produced by the substituting process may belong to the same type as the original compound. But if too large a hole is made in the supporting wall of the shop that is undergoing restoration, or if the eradication of the rubble is carried too far, the whole edifice may fall about the ears of the workmen. So, too, processes of chemical substitution may change into processes of complete disintegration, the original compound may be broken up, and compounds may be produced which differ radically from it. And, finally, when the hole has been made in the wall of the shop, and the bricks have been cleared out, and the place has been prepared for the new beam, a strong and rigid beam must be put in, else the weight pressing on it will crush the new support, and the purpose of the substitution will be defeated. Similarly, not any element, and not any group of elements, in a compound can be substituted by any other element or group; that which is substituted must be chemically like that whose place it occupies, else the whole edifice will topple over.

Let us consider some cases of substitution, with the object of attaining a clearer understanding of this conception which was declared by Liebig to be the foundation of organic chemistry. If a mixture of alcohol and oil of vitriol is heated in a flask connected with a condensing apparatus, and alcohol is allowed to trickle very slowly into the hot mixture, ether, which is a liquid with a pleasant odour, distils over. If ether is digested with water alcohol is reproduced. If alcohol is heated for some time with acetic acid (the acid of vinegar) a liquid with a markedly ethereal odour is produced. And, finally, it is possible by various reactions to pass from alcohol to several other liquid compounds all of which have more or less ethereal odours. Liquids which smell alike are not necessarily chemically alike; but similarity of odour *may* go with similarity of other properties and of composition. The various pleasantly smelling liquids obtained by reactions between alcohol and different compounds are purified, by distilling each until it boils at a constant temperature, and are then analysed quantitatively, and the results are expressed by indicating the number of combining weights of each element that are united in each compound.

It may be well to indicate by an example the method whereby the results of the analysis of a compound are expressed in terms of the numbers of combining weights of the different elements in the compound. Take alcohol; analyses shew that the percentage composition of this compound is

Carbon	52·2
Oxygen	34·8
Hydrogen	13·0
	100·0

The combining weights of carbon, oxygen, and hydrogen are 12, 16, and 1 respectively. Alcohol is composed of a certain, whole, number of combining weights of each of these elements; how many combining weights of each must there be that the following equation may be satisfied?

$(12 \times n) : (16 \times m) : (1 \times p) = 52{\cdot}2 : 34{\cdot}8 : 13.$

n = number of combining weights of carbon;
m = ,, ,, ,, oxygen;
p = ,, ,, ,, hydrogen.

The first thing to be done is to divide the number expressing the weight of each element in 100 parts by weight of the compound by the combining weight of the element. The results of doing this are:—

$\frac{52{\cdot}2}{12} = 4{\cdot}35$ combining weights of carbon;
$\frac{34{\cdot}8}{16} = 2{\cdot}17$,, ,, oxygen;
$\frac{13}{1} = 13$,, ,, hydrogen.

These results must now be expressed in whole numbers. Dividing the smallest number, 2·17 (the number belonging to oxygen), into each of the others, we have

$\frac{4{\cdot}35}{2{\cdot}17} = 2$; and $\frac{13}{2{\cdot}17} = 6$ (almost exactly).

That is, whatever be the number of combining weights of oxygen, there are twice as many combining weights of carbon, and six times as many combining weights of hydrogen. In other words, the elements are combined in the ratio of one combining weight of oxygen to two combining weights of carbon, to six combining weights of hydrogen; and the simplest formula which expresses the composition of the compound is OC_2H_6.

The results of the analyses of the other pleasantly smelling liquid compounds obtained from alcohol are treated in this way; the following formulæ express some of the results: OC_2H_6 alcohol; OC_4H_{10} ether; $O_2C_4H_8$ by heating alcohol with acetic acid; $NC_2O_3H_5$ by heating alcohol with nitric acid; ClC_2H_5 by heating alcohol with hydrochloric acid; IC_2H_5 by heating alcohol with hydriodic acid.

The reactions of formation, and many other reactions, of these compounds establish close similarities between the chemical properties of the compounds; their compositions are, therefore, probably similar also. But the formulæ given above do not suggest definite resemblances of composition. Let us employ the conception of substitution. It is no good making fanciful guesses about the substitution of this element for that, or the substitution of one group of elements for some other group; the conception is useful only when the chemical reactions of a series of compounds have been thoroughly examined and classified. In the present cases we must assume the main results of such an examination.

The reactions of alcohol shew great resemblances to those of potash and soda. Now potash and soda are compounds of hydrogen, oxygen, and potassium, and hydrogen, oxygen, and sodium, respectively; these compounds are, therefore, called hydroxide of potassium and hydroxide of sodium. Potash and soda react with acids to form salts; for instance, potash and hydrochloric acid produce potassium chloride, and soda and nitric acid produce sodium nitrate. Again, there is an oxide of potassium which reacts with water to form the hydroxide (potash), and there is an oxide of sodium which reacts with water to form the hydroxide (soda). Since alcohol is like potash and soda, in its chemical reactions, it is probably a compound of hydrogen and oxygen with some element, or elements, chemically like potassium or sodium; it is probably a hydroxide. And if alcohol is a hydroxide, it will likely react with acids to form salts; moreover an oxide may exist related to alcohol in a way like that wherein oxide of potassium is related to hydroxide of potassium, and oxide of sodium is related to hydroxide of sodium. The formulæ which express the compositions of potash and soda, respectively, are KOH and $NaOH$. If alcohol is a hydroxide, analogous in composition to these compounds, the formula for alcohol, OC_2H_6, must be expressed so as to indicate the composition of a hydroxide; this may be done by writing the formula $(C_2H_5)OH$. Look at the two formulæ, KOH and $(C_2H_5)OH$; the bracket enclosing the symbols C_2H_5 in the second formula is meant to imply that two combining weights of carbon and five combining weights of hydrogen are held firmly together. The two formulæ are comparable; one is the expression, in a certain language, which may be called the language of the law of combining weights, of the composition of a hydroxide of a metal (potassium); the other is the expression, in the same language, of the composition of a hydroxide of a group of elements itself composed of two combining weights of carbon and five combining weights of hydrogen. When potassium hydroxide reacts with acetic acid the salt potassium acetate is produced; if the reaction of alcohol with acetic acid is chemically like the reaction of potassium hydroxide, we should expect a salt to be produced differing from potassium acetate in having the group C_2H_5 in place of the metal potassium. Here are the formulæ which express the compositions of the two products:—

Potassium acetate	*Acetate produced from alcohol*
$KC_2H_3O_2$.	$(C_2H_5)C_2H_3O_2$.

The composition of the compound obtained by heating alcohol and acetic acid was already expressed by the formula $O_2C_4H_8$ (see p. 128); the composition of the same compound is now expressed as $(C_2H_5)C_2H_3O_2$ But the second of these formulæ is merely what may be called a dissection of the first, adopted to bring out the similarity between the reactions of this compound and those of potassium acetate.

Sodium nitrate is produced by the reaction between sodium hydroxide (soda) and nitric acid; the formulæ which express the composition of this salt, and that of the product of reacting on nitric acid with alcohol, are

Sodium nitrate	*Nitrate produced from alcohol*
$NaNO_3$.	$(C_2H_5)NO_3$.

The compositions of sodium chloride and potassium iodide, on the one hand, and the compositions of the products of the interaction between hydrochloric, and hydriodic, acid and alcohol, on the other hand, are expressed by the formulæ ;

Sodium chloride	*Potassium iodide*	*Chloride from alcohol*	*Iodide from alcohol*
$NaCl$.	KI.	$(C_2H_5)Cl$.	$(C_2H_5)I$.

Finally, the compositions of sodium (or potassium) oxide, and ether, are expressed thus ;

Sodium oxide	*Potassium oxide*	*Ether*
Na_2O.	K_2O.	$(C_2H_5)_2O$.

Gathering together the formulæ which express the compositions of various compounds derived from alcohol, when the relations between these compounds and alcohol are looked on as similar to the relations between potash and various compounds obtained therefrom, and placing these formulæ side by side with those of the corresponding potash compounds, we have the following results.

$(C_2H_5)OH$ *Alcohol.*	KOH *potash.*
$(C_2H_5)_2O$ *Ether.*	K_2O *potassium oxide.*
$(C_2H_5)Cl$ *Ethyl chloride.*	KCl *potassium chloride.*
$(C_2H_5)I$ *Ethyl iodide.*	KI *potassium iodide.*
$(C_2H_5)NO_3$ *Ethyl nitrate.*	KNO_3 *potassium nitrate.*
$(C_2H_5)\ C_2H_3O_2$ *Ethyl acetate.*	$KC_2H_3O_2$ *potassium acetate.*

Not only are the two compounds in any one of these lines similar in chemical properties, they are also represented as having similar compositions. And the similarities of composition are brought out by supposing that the quantity by weight of a group of two elements expressed by the formula C_2H_5 can be substituted for one combining weight of the element potassium. The group C_2H_5 is called *Ethyl ;* it is composed of two combining weights of carbon in chemical union with five combining weights of hydrogen.

This group can take the place of one combining weight of potassium in various compounds without altering the general chemical characters of these compounds. The compounds of potassium formulated above are very unlike the corresponding ethyl compounds in their physical properties; for instance, the potassium compounds are all white, odourless, solids, while the ethyl compounds are all colourless, sweet-smelling, liquids. But corresponding compounds in the two series shew such distinct chemical similarities that they must be regarded as belonging to the same chemical type.

The considerations glanced at in the foregoing paragraphs lead to the recognition of the possibility of a group of elements taking the place of a single element without destroying the general chemical character of the compound wherein this substitution occurs. This recognition has been gained by applying the principle of substitution; it is indeed a part of the conception of substitution, nevertheless it is a most important advance from the earlier notion of substitution being effected by putting one element in the place of another element. The name *compound radicle* is given to a group of elements which can be, theoretically, moved from compound to compound without the breaking up of the group. A moment's consideration will show, I think, that the word *theoretically*, or some equivalent term, must be introduced into the description of the compound radicle. Compare the compounds of the element potassium with those of the compound radicle ethyl (C_2H_5). The compounds of potassium can be broken up and potassium can be isolated from every one of them; further, various elements can be added on to potassium, and the different compounds of that element can thus be produced. But the compounds of ethyl cannot be broken up in such a way that the compound radicle ethyl may be isolated; this group of elements has no existence by itself; nor can compounds of ethyl be produced by actually joining various elements on to ethyl, for ethyl cannot, so to speak, be held in the hand. The compound radicle ethyl is a theoretical conception introduced for the purpose of enabling chemists to represent similarities of properties as accompanied by similarities of composition. Grant the hypothesis, and order is palpably introduced, where, without the hypothesis, order cannot be expressed. The facts shew that order is there; but we require a language wherein the orderly facts may be expressed, and after many trials we have hit upon the language that uses the conception of the compound radicle, and the conception of the possibility of substituting compound radicles, not only for other compound radicles, but also for single elements.

When we come to speak of the theory that gives a mechanical conception of the mechanism of chemical reactions, we shall find that the notion of the compound radicle becomes clearer and more precise.

Organic chemistry is built on the foundation of the conception of substitution, and that foundation is strengthened by working in with it the subsidiary conception of the compound radicle.

It is not only in the domain of chemical science that great advances have been made by employing the notions of substitution and the compound radicle. Large and flourishing chemical industries are based on the practical applications of these conceptions; among these industries there is perhaps none so important as the manufacture of aniline colours. Because of the name "coal-tar colours," by which these dye-stuffs are often known, there seems to be a fairly widespread belief that the aniline colours are hidden in coal-tar, and that they are got out of that ugly black stuff by processes of purification. But this is quite a mistake. A colourless liquid called benzene is obtained by distilling coal-tar; when benzene is treated with concentrated *aqua fortis* (nitric acid), mixed with some oil of vitriol, an oily liquid, smelling like oil of almonds, is formed; and when this *nitro-benzene* is warmed with iron filings and acetic acid, aniline distils over. Aniline is a colourless liquid; its composition is expressed by the formula $(C_6H_5)NH_2$. The compound radicle C_6H_5 is called *phenyl*. A very large number of compounds, many of which are dyes, is prepared by substituting some of the hydrogen in the phenyl radicle of aniline by other compound radicles; compounds with dyeing properties are also produced by substituting various compound radicles for one or two of the combining weights of hydrogen represented in the formula of aniline as not forming part of the phenyl radicle. Then some of the derivatives of aniline obtained by the substitution of compound radicles for hydrogen react and produce more complex compounds, from which again definite numbers of combining weights of hydrogen, or of other elements, are removed, and their place is taken by definite quantities of more or less complicated compound radicles. And so the preparation of new compounds proceeds, one may say in every case by processes that are essentially substitutions; the relations of the compounds to one another are often extremely complex, but the principle of substitution—always remembering that a group of elements may be put in the place of a single element without changing the essential chemical character of the compound—is a guide through all the complicated wanderings.

Of course, as the number of what may be called substituted anilines increases, various subsidiary hypotheses are used as helps in determining the relations of these compounds to one another; but the guiding principle is substitution; not haphazard attempts to put this or that group in place of some other group, but regulated, orderly, substitutions based on the results of accurate quantitative experiments, wherein properties are constantly connected with composition. The performance of various processes of substitution, and the comparisons of the dyeing properties of the products with those of the parent substances, lead to suggestions that if the substituting radicle is altered, or perhaps if substitution by the same radicle is not carried quite so far, or, it may be, is carried a little further, the products so obtained will probably dye a richer tint than any of those dyes that have been tried already ; and the experiment is made, and the special tint which the new compound dyes forms the basis of other experiments.

It is evident that processes of this kind cannot be conducted except by those who have made a minute, experimental, critical study of a very large field of chemical inquiry. Unless a man is thoroughly at home in the carrying out of complicated processes of substitution among the derivatives of aniline—and hundreds of these derivatives are known to-day—it would be absurd for him to attempt the preparation of a new colouring matter by first comparing the dyeing properties and the compositions of the known compounds, then predicting, theoretically, the composition of the compound with the special colour he wants, and then setting about the practical fulfilment of his prediction. To set a man to such a task without making sure that his training fitted him for it would be like setting one who had dabbled a little with bricks and mortar to raise the roof of a large building, to substitute for the present upper row of windows in the side wall a smaller number of much larger windows, to raise the wall some feet, and then to set the roof on again. Any one who asked a man not very especially skilled in such work to undertake the change I have indicated in the building would be called a fool. And yet hundreds of attempts have been made to carry out the more difficult tasks of the chemical builder by men who profess that a little practice is worth a pound of theory

There was a time when most of the trade in aniline colours, and the dye stuffs related to them, was in the hands of English manufacturers; the trade has now become a German industry, simply because the German manufacturer has either been a trained chemist or he has had the sense to understand that the problems at the root of the industry are too complicated to be attacked by anyone who is not a trained, and a truly scientific, chemist. To attempt to gain, even in outline, any grasp of the principles on which the aniline industry rests, means to make a thorough and accurate study, in the laboratory and in the lecture-room, first of chemistry as a whole, then of organic chemistry as an especial branch of the science, and then of aniline and its derivatives and allied compounds as a peculiar department of organic chemistry. For the aniline industry is truly a chemical industry, and the note of all chemistry is change. The rules that hold good to-day will not suffice to meet the demands of the trade to-morrow. Fashion in colours changes; and the manufacturer who can supply only his few stock colours soon falls out of the running.

There is another department of applied chemistry in which the regulated use of the principle of substitution has led to astonishing results, and that is the making of new drugs with specific properties. Take, for instance, some of the more recently introduced febrifuges. The study of the reactions of quinine, and of the reactions of compounds obtained from quinine under definite conditions, has led to the establishment of certain connexions between the presence of definite compound radicles, related to one another in definite ways, and the existence of fever-abating properties. Although these studies have not yet enabled the chemist to build up quinine itself, they have enabled him to put together chemical structures, by arranging definite compound radicles in definite ways, which have marked effects on the bodily temperature of human beings. *Antipyrine* is one of these compounds, and *phenacetin* is another. It is impossible in such a book as this to attempt to describe the constitutions of these compounds; for the descriptions must be recorded in language that is meaningless to anyone other than a trained chemist. Suffice it to say that both compounds are constructed by building up certain compound radicles on the basis of nitrogen, and that the radicles are arranged in a perfectly definite manner relatively to one another. Why the building processes should be conducted in this or that particular direction; why this building stone—that is, this compound radicle—should be used rather than that; reasons for these things have been found in the study of the reactions whereby bodies with properties like those it is desired to impart to the new compounds have been broken down into their constituent compound radicles. Buildings with properties of the desired kind have been taken to pieces; the nature, that is, the compositions and the properties, of the pieces have been examined; the positions of the pieces in the original buildings have been noted; and then similar buildings have been constructed; and in many cases the new buildings have possessed the wished-for properties.

Now it has been said that those complex chemical building stones which are called compound radicles cannot be isolated (refer back to p. 133); and yet I have spoken of dissecting a compound into the compound radicles that compose it. Both statements are accurate. Only in the processes of dissection the radicles are not obtained wholly apart from combination with other things; compounds of the compound radicles are obtained, and the existence of the radicles in these compounds is inferred from the reactions of the compounds. It is this determination of the compound radicles to remain hidden that makes the conduct of definite building operations with these radicles so difficult. The chemist who is endeavouring to construct such a complicated structure as antipyrine need have a clear and penetrating imagination; he has constantly to see the inner structure of the buildings he is trying to copy, and yet he cannot isolate those building stones which it is essential for him to work with. He has, as it were, to lift his building stones with a stick, which has the peculiar property that the moment a stone is poised on it the stone and the stick become one, neither the stick nor the stone has any longer an independent existence. And when he puts the stone into its place, feeling about as best he can, the stone vanishes into the building; he only knows that the stone is there by constantly testing the whole building, perhaps a knock with his mallet gives a different sound from what he heard before the last stone was added to the building. And then, when he looks for the stick that he may lift another stone into its place, very often the stick has vanished too, and the chemist must set about making a new one.

The chemical building trade, at least in its more refined branches, is even more difficult than the illustration I have used would lead one to expect. The chemist is all the time working with hypothetical building materials. The elements are definite kinds of matter that can be touched and handled, and put together, and separated; but comparatively little is done by working with the elements in the erection of the complicated buildings of organic chemistry. There, groups of elements are the units of the edifices; and on scarcely one of these building units is the chemist able confidently and definitely to lay his hands. He can only conjecture that they are in the buildings, because by no other hypothesis has he been able to picture to himself the existence of an orderly arrangement of the parts of these buildings; but the orderly properties of the buildings force him to postulate for them an orderly composition also.

The chemist has to guide his operations by the light of an hypothesis; mere facts are quite insufficient for him. And he has to state that hypothesis in an exceedingly symbolic language, a language which makes constant use of such abstract conceptions as *substitution* and *compound radicle.* It is true that the language gains in clearness and accuracy as it developes; but it gains in these qualities by founding itself on another hypothesis, that, namely, of the atom and the molecule. It is the laboratory which saves chemistry from artificiality. It is the constant contact with acids, and alkalis, and salts, and evil smelling and sweetly odorous definite substances; it is the constant handling of distilling apparatuses, and flasks, and beakers, and measuring vessels, and balances; it is this blessed walking on the solid earth that gives an intense reality to the science which is concerned with abstract conceptions of composition and properties, and which is obliged to clothe its conceptions in the imagery of a symbolic language.

CHAPTER VIII.

THE ATOM AND THE MOLECULE.

THE especial problem of chemistry is to trace definite connexions between the compositions and the properties of compounds. The compositions of compounds are stated in terms of the elements which unite to form these compounds, and which can be obtained by disintegrating the compounds; and the quantities of the elements which are united in the compounds are expressed as numbers of combining weights of the elements. We found in the last chapter that certain connexions between some of the chemical properties of many compounds can be suggested by the formulæ which express the compositions of these compounds, only on the assumption that certain groups of elements behave like single elements, and that such groups, or compound radicles as they are called, can be substituted for one another, or for single elements, without destroying the general chemical type to which the compounds belong. This result might be stated in general terms by saying that the primary notion of composition, as expressed in quantities of individual elements, must be modified to include the notion of the compound radicle, in order that the observed properties of compounds, and especially of carbon compounds, may be represented as connected in definite ways with the compositions of the same compounds.

Let us now turn back to the first building up of a compound of peculiarly organic origin from materials derived from inorganic sources; let us revert to the synthesis of urea by Wöhler in 1828 (see p. 119). The substance from which urea was immediately produced by Wöhler was a salt called *ammonium cyanate*. There is one very peculiar thing about these two compounds, urea and ammonium cyanate; both have absolutely the same elementary composition. Each compound contains 46·66 *per cent.* of nitrogen, 26·67 *per cent.* of oxygen, 20·0 *per cent.* of carbon, and 6 67 *per cent.* of hydrogen: the composition of each is expressed by the formula N_2OCH_4. But the properties of the two compounds differ in the most marked way; they belong to wholly different classes of compounds. The direction wherein some explanation of this phenomenon seems likely to be found is the application to it of the conception of the compound radicle. Is ammonium cyanate constructed by putting together groups of elements different from those which form urea? Before attempting to find an answer to this question we must have some clearer notions than we now possess about the putting together of elements and groups of elements; and the only way in which such clearer notions can be gained is by framing a consistent hypothesis regarding the mechanism of chemical reactions.

If the expressions that have been used in preceding chapters about chemical buildings, the construction of chemical edifices, and the like occurrences, are considered carefully, a tacit assumption will be found running through them to the effect that each element is composed of small, but definite, portions of matter, all of which have the properties of that element. The illustrations that have been employed to throw light on processes of chemical construction, as well as the language that has been used to express these processes have almost taken for granted, although they have not expressly stated, that all kinds of homogeneous substances have a grained, and not a jelly-like, structure. It is into this subject, the structure of definite kinds of matter, that we must now inquire.

About the beginning of the century a Quaker gentleman, called John Dalton, living in Manchester, who had been a schoolmaster but at that time supported himself by giving lessons in mathematics and natural philosophy, was thinking a great deal about the pressure of gases, the expansion of gases by heat, and the solubilities of gases in different liquids Being a man of vivid imagination in all that pertained to the scientific questions which interested him most, Dalton was in the habit of seeing, with his mind's eye, the ultimate structure of the gases that formed the subject of his inquiries. He says, "A vessel full of any pure elastic fluid [that is, any gas] presents to the imagination a picture like one full of small shot." But Dalton was not contented with picturing to himself what he conceived to be the structure of the gases he was thinking about; he tried to connect that structure with the properties of these gases. Now he found, from his experiments and those of others, that water dissolves different volumes of different gases at the same temperature and pressure; he thought of the particles of the various gases, like particles of small shot, being pushed between the particles of water, until there was no room for more at that pressure and temperature; but, he asked, if this is what happens, why does not water dissolve the same volume of all gases when the temperature and pressure are kept the same? To this question Dalton gave an answer which has been of enormous importance to chemistry:—"I am nearly persuaded that the circumstance depends upon the weight and number of the ultimate particles of the several gases, those whose particles are lightest and single being least absorbable, and the others more, according as they increase in weight and complexity." And to that answer he added a statement which has been even more important in aiding the advance of chemistry than the answer itself:—"An inquiry into the relative weights of the ultimate particles of bodies is a subject, so far as I know, entirely new. I have lately been prosecuting this inquiry with remarkable success. The principle cannot be entered upon in this paper, but I shall just subjoin the results, as far as they appear to be ascertained by my experiments." Dalton appends a "*Table of the relative weights of the ultimate particles of gaseous and other bodies.*" That list is the first example of what we should now call a "*Table of atomic weights.*"

When Dalton pictured to himself "a vessel full of a gas as like one full of small shot," he was doing what had been done by Greek philosophers about 2500 years before him; but when he connected a definite and measurable phenomenon with differences in the weights of the ultimate particles of different bodies, and, more especially, when he shewed (in later publications than that I have quoted from) how to determine the relative weights of these hypothetical ultimate particles, he converted the interesting speculation of the Greeks into a scientific and science-producing theory.

I cannot enter into the reasoning whereby Dalton was led in the first instance to assign certain relative values to the weights of the ultimate particles, or atoms, of various elements; the reasoning, and the experiments which supplied the data, were rather physical than chemical. But at a slightly later time Dalton enunciated the law of combining weights as a necessary deduction from his theory of the structure of matter; and then the reasoning whereby the relative weights of the atoms of the elements were determined ran somewhat on the following lines.

The theory began by assuming that every definite kind of matter, that is, every element and compound, has a grained structure', of course, if all elements and compounds have a grained structure, mixtures must have a similar structure. But what exactly is meant by a *grained structure?* Merely that any definite substance fills space as apples fill a barrel, and not as jelly fills a mould; that if one could magnify enormously a small portion of any definite substance, say water, one would see an immense heap of extremely small particles of water piled together with interstices between them; a grained structure means exactly what Dalton's picture of a vessel full of small shot means Then the theory asserted that every individual grain of any definite kind of matter is exactly like every other grain of the same kind of matter, alike in weight and in all other properties. Dalton called these minute grains of elements and compounds *atoms*, but as he applied the term both to elements and compounds it is evident that he did not use the term in its strict, etymological, meaning of *something which cannot be cut.* We are assured that Dalton was very fond of clenching a chemical argument with the statement: "Thou knowest thou canst not cut an atom." He evidently meant,--you can't cut an atom without destroying the essential properties of the substance; if you cut an atom of water, for instance, you have no longer water, but oxygen and hydrogen. Dalton evidently thought of the atom of an element as, practically at any rate, indivisible. It is well to notice here that the Daltonian theory does not concern itself with the question, which lies outside the domain of physical science, of the finite or infinite divisibility of matter. Granting, then, that matter has a grained structure, that all the grains of any one kind of matter are identical in weight and other properties, and that these grains, or atoms, cannot be cut without the disappearance of the special kind of matter of which each grain is a minute portion, the theory went on to assert that the chemical union of elements consists in the joining of definite numbers of atoms of elements into more complex atoms, which are atoms of compounds; and that chemical interaction between compounds consists in, first, the breaking up of the atoms of the reacting compounds, and then the rearrangement of the elementary atoms so produced in new combinations, that is, so as to form new compound atoms.

Having thus cleared the ground, let us see how the relative weights of the atoms of the elements were determined after the enunciation of the law of combining weights. As hydrogen is the lightest kind of matter known, that element was taken as the standard in terms of which the relative weights of atoms were to be expressed; the weight of an atom of hydrogen was called one, and the object was to find out how many times an atom of each element was heavier than an atom of hydrogen. Take the case of the union of hydrogen and oxygen; weights of these elements combine in the ratio of one part of hydrogen to eight parts of oxygen; but the act of combination consists, according to the theory, in the joining of atoms of the two elements; therefore, one atom of oxygen weighs eight times more than one atom of hydrogen; and, as the atomic weight of an element is the number which tells how many times an atom of that element is heavier than an atom of hydrogen, the atomic weight of oxygen is eight. Or take the case of hydrogen and chlorine; the weights of these elements which combine stand to one another in the ratio of 1 to 35·5; therefore, as the act of combination is asserted by the theory to consist in the joining of atoms of hydrogen, all of which are identical in weight and other properties, with atoms of chlorine, all of which are also identical in weight and other properties, but all of which differ in weight as well as in other properties from atoms of hydrogen, it follows that one atom of chlorine is 35·5 times heavier than one atom of hydrogen, in other words, that the atomic weight of chlorine is thirty-five and a half. Or take the case of sulphur; inasmuch as the weights of sulphur and hydrogen which combine are in the ration of 16 to 1, it follows, by reasoning similar to that already used, that the atomic weight of sulphur is sixteen.

The relative weights of the atoms of the elements, that is, the atomic weights of the elements, were obtained by the use of the Daltonian theory in exactly the same way as the relative values of the combining weights of the elements were obtained; both atomic and combining weights were stated in terms of hydrogen as unity, because hydrogen weighs less, bulk for bulk, than any other element. Indeed, it is worthy of note that the two conceptions expressed by the terms atomic weight and combining weight were introduced into chemistry at the same time and by the same man.

A close examination of the reasoning whereby it has been asserted in the preceding paragraphs that values were found by Dalton for the atomic weights of the element , will disclose a large assumption which was purposely slurred over in these paragraphs. Turn again to the case of oxygen ; the atom of oxygen was said by Dalton to weigh 8 times more than the atom of hydrogen, because 8 parts by weight of oxygen combine with 1 part by weight of hydrogen. In drawing this conclusion the assumption has evidently been made that when oxygen and hydrogen combine a single atom of either element is joined to a single atom of the other element. Suppose Dalton had chosen to assume that two atoms of hydrogen combine with one atom of oxygen, then, as the weights of the elements that combine are in the ratio of 8 to 1 (oxygen to hydrogen), and as it is asserted that one atom of oxygen combines with two atoms of hydrogen, it is evident that each atom of oxygen must weigh 16 times as much as each atom of hydrogen (16 : 2 = 8 : 1). On this assumption, the atomic weight of oxygen would be 16, and not 8 as determined by Dalton.

Suppose, again, that Dalton had assumed that two atoms of oxygen combine with one atom of hydrogen, then the conclusion must have followed, from the fact that eight parts of oxygen by weight combine with one part of hydrogen, that the atom of oxygen is four times heavier than the atom of hydrogen, and on this assumption the atomic weight of oxygen would be four. To arrive at the value 8 for the atomic weight of oxygen, Dalton made the simplest of all the possible assumptions regarding the numbers of atoms of hydrogen and oxygen that combine, the assumption, namely, that the atoms of these elements combine in the ratio of one to one.

Look for a moment at the case of nitrogen. Dalton said that because 4·66 parts by weight of nitrogen combine with one part by weight of hydrogen, the atomic weight of nitrogen is 4·66; the assumption was implicitly made that atoms of these two elements combine in the ratio of equality. But at a later time the atomic weight of nitrogen was changed to 14, that is, to 4·66 × 3; and it was then asserted that three atoms of hydrogen combine with a single atom of nitrogen, to form a compound atom of ammonia (14 : 3 = 4·66 : 1).

Why should the simplest possible assumption regarding the numbers of combining atoms be made in some cases, and a more complex assumption be accepted in other cases? Briefly put, the principle which guided chemists was this; make the simplest assumption you can that is in keeping with the observed reactions of the compound you are dealing with. If it is assumed, for instance, that one atom of hydrogen combines with one atom of oxygen to form a compound atom of water, then it should not be possible to remove part of the hydrogen, or part of the oxygen, from the water-atom; if there is only one atom of each element in the compound atom of water, then, if hydrogen is taken away, or if oxygen is removed, from water, all the hydrogen must be taken away, or all the oxygen must be removed; because an atom of an element is, by definition, a quantity which cannot be divided into smaller parts of the same substance. Now, they said, experiments prove that the hydrogen in ammonia can be removed in three equal portions, but that if any nitrogen is taken away from ammonia all the nitrogen must be taken; therefore, as the chemical reactions of ammonia consist, in the first instance, in breaking up the atom of this compound, it is evident that there must be three atoms of hydrogen, but only a single atom of nitrogen, in the compound atom of ammonia; and therefore as the weights of the two elements that combine to form ammonia are in the ratio of 1 to 4·66 (hydrogen to nitrogen), it follows that the atomic weight of nitrogen must be fourteen.

The principle which guided chemists in selecting one value, from several possible values, for the atomic weight of an element is a principle that is constantly used in all branches of natural science, and in all affairs of ordinary life; it is, make the simplest assumption that is in keeping with the facts, and act on that assumption.

But this principle could not be applied to the determination of atomic weights either with sufficient ease or sufficient exactness. Each case had to be discussed elaborately; numbers of subsidiary facts had to be marshalled, and compared with other similar facts, or contrasted with other dissimilar facts. The theory certainly laid down a principle capable of universal application; but the application did not go far enough; it left chemists in doubt as to which of several possible values for the atomic weight of an element was the correct value. What the theory did was to enable a value to be found which, or a whole multiple, or a whole submultiple, of which, was the value for the atomic weight. It was only necessary to determine the weight of an element which combined with one part by weight of hydrogen; then this weight, or a whole multiple of this weight, or it might be a whole sub-multiple of this weight, was the relative weight of the atom of the element in question in terms of the weight of the atom of hydrogen taken as unity. In the case of an element which refused to combine with hydrogen, all that need be done was to use oxygen as a go-between, and to find the weight of the element which combined with 8 parts by weight of oxygen; for 8 parts by weight of oxygen combine with 1 part by weight of hydrogen.

But chemists wished to be able to decide which of several possible values was the correct value for the atomic weight of each element. Turn again to the case of oxygen. If it is assumed that one atom of oxygen combines with one atom of hydrogen, then, from the experimental data, the atomic weight of oxygen must be 8, and the compound atom of water must weigh 9 times more than the atom of hydrogen; if it is assumed that two atoms of oxygen combine with one atom of hydrogen, then the atomic weight of oxygen must be 4, and the compound atom of water must weigh 9 times more than the atom of hydrogen; and if it is assumed that one atom of oxygen combines with two atoms of hydrogen, the atomic weight of oxygen must be 16, and the compound atom of water must weigh 18 times more than the atom of hydrogen. If a method can be found for determining the relative weight of the compound atom of water, an important step will have been taken towards determining the relative weight of the atom of oxygen also; and if the relative weights of a number of compound atoms, all of which contain oxygen, can be determined, data will have been obtained for finding the true value for the atomic weight of oxygen.

The shortcoming in the theory he had enunciated was felt, and plainly acknowledged, by Dalton. He says that his object was, not only to ascertain "the relative weights of the ultimate particles both of simple and compound bodies," but also to determine "the number of simple elementary particles which constitute one compound particle, and the number of less compound particles which enter into the formation of one more compound particle." In order to attain these objects Dalton laid down certain rules regarding the complexities of compound particles, which helped him, and others, to arrive at consistent conclusions regarding the relative weights of the atoms of the elements.

But rules were not sufficient; an all-embracing general principle was required, whereby the relative weights of the atoms of compounds could be determined. Such a principle was supplied in the year 1811 by the Italian naturalist, Avogadro.

Avogadro remarked two things. First he said there must be some reason for the fact that when gaseous elements or gaseous compounds react to produce new gases, there is an extremely simple relation between the volumes of all the gaseous bodies concerned; for instance, a pint of oxygen combines with two pints of hydrogen to form two pints of steam, and two pints of hydrochloric acid gas are formed by the union of a pint of hydrogen with an equal volume of chlorine. Then he noticed the undesirability of applying the same term, the term *atom*, to an extremely minute portion of an element, and also to an extremely minute portion of a compound; for what was called an atom of a compound could be, and constantly was, shattered into parts, whereas an atom of an element was, by definition, that extremely small quantity of the element which was never broken up in any of the reactions wherein the element took part. Avogadro said in effect:—Let us recognise two orders of extremely small particles; let us speak of the *molecule*, and also of the *atom*; let the molecule, either of an element or a compound, be the smallest portion of the body which exhibits those properties which we recognise when the body is regarded apart from the action on it of other bodies; let the term atom be applied to elements only, and let it mean one of those parts of an elementary molecule into which that molecule is shattered when it reacts chemically with other molecules. Avogadro pictured the molecules of elements as themselves structures; he thought of these structures as remaining intact in all those changes we call physical; and he represented chemical action between elements as consisting, in the first place, in the falling to pieces of the molecules of those elements, and then in the arrangement of the parts of molecules so produced, that is, in the arrangement of the atoms, in new combinations, that is, new molecules. And he represented chemical action between compounds by an exactly similar mechanism; he pictured compound molecules clashing together, and falling to pieces, and then he saw the elementary atoms rearranging themselves in new groups, and so producing either the molecules of new compounds, or, if atoms of the same kind should coalesce, the molecules of elements. By his recognition of the molecule, and the atom, Avogadro removed the distinction between the mechanisms involved in chemical reactions between elements on the one hand and compounds on the other hand, which the Daltonian use of the term *atom* had tended to foster. Then, to account for the great simplicity which experiments had proved to exist in the relations between the volumes of gases that react chemically, Avogadro said:—*Equal volumes of elementary or compound gases, measured at the same temperature and pressure, contain equal numbers of molecules.* This statement has been known for many years as *Avogadro's Law;* it is of paramount importance in chemistry.

Avogadro enunciated the words I have put into italics as an empirical statement; since his day it has been raised to the rank of a necessary deduction from a general dynamical theory of the constitution of homogeneous gases. It is quite impossible in this place to go into the reasoning whereon this deduction from the dynamical theory of gases rests; all that can be said is that the reasoning is mathematical and dynamical. The truth and universal applicability of Avogadro's law are really assumed in chemistry.

Equal volumes of gases, equal numbers of molecules. Here is a method for doing what Dalton recognised must be done, but which he failed to do, a method for finding the relative weights of the molecules, or, as Dalton would have said, the compound atoms, of all compounds which can be gasified without decomposition. And the method is also applicable to elements; provided an element can be gasified without undergoing chemical change, the molecular weight of that element can be determined by applying the law of Avogadro.

Let us see how the law is used to accomplish this end. All the molecules of the same gas are asserted to have the same weight and to be identical in properties. Suppose a pint of hydrogen, a pint of oxygen, and a pint of dry steam, are weighed at the same temperature and pressure; and the results are stated so as to express how many times heavier than the lightest of the three the other two are, that is, how many times the pint of oxygen, and how many times the pint of steam, is heavier than the pint of hydrogen. Those numbers which express the relative weights of equal bulks of the three gases must also express the relative weights of equal numbers of the three kinds of molecules; for equal volumes of gases contain equal numbers of molecules. Now, as all the molecules of hydrogen weigh the same, and as all the molecules of oxygen weigh the same, and as all the molecules of steam weigh the same, the numbers which express the relative weights of equal numbers of molecules of hydrogen, oxygen, and steam, respectively, must also express the relative weights of single molecules of these three kinds of matter. In other words, the molecular weights of the three gases are expressed by the numbers which tell the relative weights of equal volumes of these gases, provided these volumes are made equal at the same temperature and pressure, for the volume of a gas changes very much with changes of temperature or pressure.

Let us take the actual experimental results in the cases we are examining. Experiments prove that any volume of oxygen weighs sixteen times more than the same volume of hydrogen, temperature and pressure being the same; and experiments prove that any volume of dry steam weighs nine times more than the same volume of hydrogen, at the same temperature and pressure. Therefore the molecule of oxygen is sixteen times heavier than the molecule of hydrogen. In other words, *if the molecular weight of hydrogen is set down as one*, then the molecular weight of oxygen is sixteen, and the molecular weight of steam, or water-gas as it may be called, is nine.

Hydrogen is chosen as the standard substance because it is the lightest kind of matter known. The molecular weight of a gas is the number which tells how many times a molecule of that gas is heavier than a molecule of hydrogen. And the molecular weight of a gas is determined by finding how many times a determinate volume of that gas is heavier than the same volume of hydrogen measured at the same temperature and the same pressure.

Now supposing, let us say for reasons of convenience, that it is decided to represent the molecular weight of hydrogen by the number *two*, rather than by unity. Then, in the cases we have examined, the molecular weight of oxygen would be expressed by the number 32, and the number 18 would express the molecular weight of water-gas; for 1 : 16 : 9 = 2 : 32 : 18. Supposing that the molecular weight of hydrogen is taken to be *three*, then the molecular weights of oxygen and water-gas must be expressed by the numbers 48 and 27 respectively. If it should be found convenient to call the molecular weight of hydrogen *one half*, it is evident that the number 8 must be used to represent the molecular weight of oxygen, and the number 4½ to represent the molecular weight of water-gas.

As a matter of fact, the molecular weight of hydrogen is always expressed by the number *two*;

and therefore the molecular weights of oxygen and water-gas are expressed by the numbers 32 and 18 respectively. Now why should the molecular weight of hydrogen, which it is agreed shall be the standard element whereto all other molecular weights shall be referred, be represented by the number two rather than by the number one? It is to be remembered that we have agreed to express the atomic weights of all elements by numbers which tell how many times heavier each atom is than the atom of hydrogen, and that in assigning values to these atomic weights we have agreed to take the atom of hydrogen as unity; in other words, we have agreed to express all atomic weights on the scale of hydrogen, calling the weight of an atom of hydrogen one. Were we then to express all molecular weights on the scale of hydrogen, with the molecular weight of hydrogen taken as one, we should obtain the same numbers for the molecular, as for the atomic, weights of the elements. Now, granting Avogadro's law, it can be shewn that the molecular weights of some elements at any rate are not the same as the atomic weights of these elements; it can be shewn that when such elements react chemically their molecules are shattered into smaller parts. In the case of hydrogen, it can be shown that the molecule of this element is broken into two parts in many chemical reactions. But if the molecule of hydrogen is composed of two parts, and if the parts of the molecule of an element are to be called atoms, then the molecular weight of hydrogen must be represented by a number twice that which represents the atomic weight of hydrogen; now we have agreed that the atomic weight of hydrogen shall be represented by the number one; hence the molecular weight of hydrogen must be represented by the number two.

The proof that the molecule of hydrogen separates into two parts during many chemical actions, rests upon, and assumes the validity of, the law of Avogadro. Consider one especial reaction of hydrogen; namely, its combination with the gaseous element chlorine to form the gaseous compound hydrochloric acid. Experiments prove that equal volumes of hydrogen and chlorine combine to form a volume of hydrochloric acid gas that is equal to twice the volume of the hydrogen, or twice the volume of the chlorine, used; and that hydrochloric acid gas is composed of hydrogen and chlorine, and of these elements only. Apply Avogadro's law to these facts. *Equal volumes, equal number of molecules.* Whatever may be the number of molecules of hydrogen, twice as many molecules of hydrochloric acid gas have been formed; therefore every molecule of hydrogen has produced, by uniting with chlorine, two molecules of hydrochloric acid gas, for one volume of hydrogen has produced two volumes of hydrochloric acid. Therefore every molecule of hydrogen has separated into two parts (it is just possible that each molecule may have separated into more than two parts); and each half molecule has combined with a half molecule of chlorine to produce a molecule of hydrochloric acid gas. Now these fractions of the molecule of hydrogen are called atoms of hydrogen; and as each molecule of hydrogen has separated into two atoms, the molecular weight of hydrogen is evidently double its atomic weight; but the atomic weight is, by agreement, to be taken as unity, therefore the molecular weight of hydrogen must be expressed by the number two.

Of course the argument applies to chlorine also; had we fixed on chlorine as the standard element for atomic and molecular weights we should have called the atomic weight of that element one, and, from the foregoing facts and reasoning, we should have set down the molecular weight as two.

Many other reactions between hydrogen and other gaseous elements lead to the same conclusion, namely, that the molecular weight of hydrogen is twice its atomic weight; in other words, that the molecule of hydrogen is broken into two parts, or atoms, during many chemical reactions, and that these atoms enter into union with other atoms to form new molecules.

The molecular weights of several elements, and of many compounds, have been determined by the use of Avogadro's law. And this law has also enabled the atomic weights of the greater number of the elements to be obtained. It is not easy to follow the method whereby the application of the law leads to determinations of atomic weights; but an illustration may put the reader in the way of understanding the principle of the method. Let us choose oxygen. The relative densities, referred to hydrogen, of a number of compounds of oxygen in the gaseous state have been determined; when the number expressing how many times each of these gaseous compounds of oxygen is heavier than an equal bulk of hydrogen is multiplied by two, the result is the molecular weight of that compound. All these compounds have been analysed, and the quantity of each element has been expressed as so much of that element by weight in one molecular weight of the compound. Then the smallest quantity by weight of oxygen found in a molecular weight of any one of these compounds is taken as the atomic weight of oxygen. For instance, carbonic acid gas is found to be 22 times heavier than hydrogen, bulk for bulk; therefore the molecular weight of this gaseous compound is 44: the analysis of carbonic acid gas shows that it is composed of 27·27 *per cent.* of carbon, and 72·73 *per cent.* of oxygen; if these numbers are stated as parts by weight of carbon and oxygen, respectively, *per* 44 parts by weight of the compound, the results are, 12 parts of carbon and 32 parts of oxygen. That is to say, in the quantity of carbonic acid gas expressed by the molecular weight of that compound, there are 32 parts by weight of oxygen (and 12 parts by weight of carbon). Now, no molecule of a compound of a certain element can contain less than a single atom of that element, although the molecule *may* contain several atoms of the element; this follows from the conception of the atom as the minute portion of an element the division of which into parts, if that could be accomplished, would be attended by the production of kinds of matter entirely different from the element. Hence in the present case the atomic weight of oxygen cannot be greater than 32. Another compound of oxygen is dealt with in the same way as carbonic acid gas. Suppose water to be the compound chosen. Water-gas is found to be nine times heavier than hydrogen; hence the molecular weight of water-gas is 18. Analysis shows that 18 parts by weight of water are composed of 16 parts of oxygen, and two parts of hydrogen; therefore, the atomic weight of oxygen cannot be greater than 16, although it may be a whole sub-multiple of that number. Other compounds of oxygen are examined in the same way; and the final result is that less than 16 parts by weight of oxygen has never been found in the quantity of any compound of oxygen which is expressed by the molecular weight of that compound. The atomic weight of oxygen is therefore taken to be 16.

Sufficient has been said to indicate, not to explain thoroughly, the meanings of the terms atom and molecule. The atomic and molecular theory declares that matter has a grained structure; that were our eyesight keen enough we should see that every piece of each definite kind of matter has a structure, like a brick wall, or a company of soldiers, or a heap of apples, or a roomful of cricket balls, or a bottleful of small shot. The theory calls these minute portions of homogeneous matter molecules; it asserts that all the molecules of any particular element or compound are identical in weight and in all other properties, and that the properties of any quantity of the element or compound are the properties of the molecules of that element or compound. The theory bids us think of the molecules as always moving about; moving fairly freely, but knocking against each other now and again, when the body is in a state of gas; moving less freely when the body is a liquid; and packed tightly, with but little freedom of motion, when the body is a solid. As long as the molecules of an element, or compound, merely change their rates of motion, but are neither disintegrated, nor enter into union with other molecules, the theory says that physical action only is taking place. But when a molecule of one kind collides with a molecule of another kind in such a way that, either the molecules are shattered and their parts pair off in new combinations, or the molecules swing together as a single, more complex molecule, then, according to the theory, chemical action has occurred.

The molecules of elements, as well as those of compounds, may be disintegrated by the violence of their collisions, or by some other cause: but in most cases, at any rate, these parts, these fragments of molecules tend to coalesce; sometimes the old portions join hands again, and the molecules that were shattered are re-formed; more frequently new combinations of partners are formed, and new kinds of molecules are produced. If the molecule of an element has parts, these parts are all exactly alike in weight and all other properties. The molecule of a compound has as many kinds of different parts as the number of the elements that make up that compound.

When molecules are completely disintegrated the parts of the molecules are called atoms. The properties of an element considered apart from other kinds of matter—for instance, the specific gravity, the electrical properties, the expansion by heat, the colour, and so on—are the properties of the molecules of that element; but, as the molecules are separated into their atoms when chemical change occurs, the chemical reactions of the element are conditioned by the properties of the atoms of that element. Moreover, as the moment an elementary molecule is divided, the atoms tend to join into groups, either by uniting with atoms like themselves to re-form the elementary molecules, or by combining with other kinds of atoms to produce compound molecules, the chemical properties of an element are only exhibited when that element acts on, and is acted on by, other kinds of homogeneous matter. And what is true of the molecule of an element is true also of the molecule of a compound; the chemical properties of the compound are exhibited only when the molecule is broken up, or when it unites with other molecules.

No atom has ever been divided; if an atom were divided—the theory does not say whether the cutting of an atom is, or is not, possible—kinds of matter would be produced quite different from the element whose atom was separated into parts. The atom is the ultimate particle of matter with which the chemist has to deal, at present at any rate. Chemistry recognises how changes take place in combinations of these unchanging particles.

It would not be difficult to show that the law of combining and reacting weights, which is the generalised result of the study of the compositions of homogeneous kinds of matter (see p. 66), follows necessarily from the postulates of the atomic and molecular theory; but I leave this deduction to the imaginative common sense of the reader.

Some one may say:—What of the other theory; the theory that any apparently homogeneous matter is truly homogeneous throughout; that matter has not a grained but a jelly-like structure? To such a person I would reply—try the jelly theory. It has been often tried; attempts have been made to explain the observed properties of matter by its aid; but it breaks down at once. The first test, and the final test, of every scientific theory is: Does it work? The jelly theory of matter does not work.

The molecule then has itself a structure; it is built up of parts, of atoms; and these parts, one is forced to admit, are arranged in a definite way relatively to one another. The conception of the molecule, like so many chemical conceptions, is essentially that of a building. And this is the part of the subject which we must now go into a little more deeply. Let us recall Wöhler's synthesis of urea (see p. 119). By heating ammonium cyanate to 100° Wöhler obtained urea. But ammonium cyanate and urea have identical compositions; the composition of both is expressed by the formula N_2OCH_4. The molecule of ammonium cyanate is composed of two atoms of nitrogen, one atom of oxygen, one atom of carbon, and four atoms of hydrogen; and the molecule of urea is composed of the same numbers of the same atoms. How, then, can the properties of the two molecules be different from one another? It is easy to see that the properties of a molecule must depend on the properties of the atoms that compose it, and on the numbers of each kind of atoms. But the case of ammonium cyanate and urea shews that there is a third conditioning circumstance. What can that circumstance be except the arrangement of the atoms that compose the molecule? But the consideration of the structure of molecules demands a chapter to itself.

CHAPTER IX.

MOLECULAR ARCHITECTURE.

THE process of forming a chemical compound from two or more elements has been likened in these pages to the construction of a building. We must now accustom ourselves to think of the formation of a chemical building as the putting together of definite numbers of exceedingly minute pieces of definite kinds of matter, which pieces are called atoms, and as resulting in the production of a more complex, but still extremely minute, piece of matter, which is called a molecule. And although the properties of the building are very different from the properties of the stones, or bricks, used in its construction, nevertheless we must regard the properties of the molecule as conditioned by, firstly the properties, secondly the numbers, and thirdly the arrangement, of the atoms which have been built into that molecule.

The molecules which the chemist builds by joining atom to atom are exceedingly minute. We do not know the size of a molecule; but there are many lines of reasoning, on different classes of facts, all of which point to the conclusion that the smallest portion of a definite kind of matter, say of water or iron, that can be seen by a very efficient microscope, is composed of not less than sixty million, and not more than one hundred million, molecules.

I have tried, in Chapter VIII., to indicate the kind of facts, and the nature of the reasoning on these facts, which lead chemists to definite conclusions regarding the number of atoms of each kind that go to form the molecule of any particular sort of matter. But in what directions shall chemists look for guidance when they attempt to frame a consistent and satisfactory picture of the arrangement of those surpassingly small pieces of matter which, when put together, produce a thing so minute that it must be magnified from sixty to one hundred million times before it is visible? The task may seem impossible, but it has been accomplished.

It is to be remarked that the chemist's task is not, at present, to discover what is the arrangement of the atoms in this or that molecule; that problem he does not attempt, as yet, although some day he expects to see the molecule with one of the many eyes wherewith the accurate study of nature supplies him: what he has to do now, as I have said, is to form a satisfactory and consistent mental image of the arrangement of the atoms in the molecules of the various elements and compounds the study of which is the business of chemistry. The image which the chemist forms must be clear, self-consistent, in keeping with the facts that are known, and suggestive of facts to be investigated; in a word, he must construct a scientific theory of the structure of molecules.

It would be absurd in such a book as this to attempt anything beyond the slightest sketch of the gradual building up of the theory of molecular architecture. If I can incite a few readers of this book to go more deeply into the matter, and if I am able to start them on the right path, I shall have done all I can legitimately hope to do here. Consider the four compounds—hydrochloric acid gas, water gas, ammonia gas, and marsh gas; the compositions, the molecular weights, and the number of atoms in the molecules, of these four gaseous compounds are expressed by the four formulæ, HCl (hydrochloric acid gas), H_2O (water gas), H_3N (ammonia gas), and H_4C (marsh gas). An atom of the element chlorine combines with *one* atom of the element hydrogen to form the compound molecule of hydrochloric acid gas; an atom of the element oxygen combines with *two* atoms of hydrogen to form the compound molecule of water gas; an atom of the element nitrogen combines with *three* atoms of hydrogen to form the compound molecule of ammonia gas; and an atom of the element carbon combines with *four* atoms of hydrogen to form the compound molecule of marsh gas. No compound of chlorine is known in the molecule of which one atom of that element is combined with more than one atom of hydrogen; no compound of oxygen is known in the molecule of which one atom of that element is combined with more than two atoms of hydrogen; no compound of nitrogen is known in the molecule of which one atom of nitrogen is combined with more than three atoms of hydrogen; nor is any molecule known of a compound of carbon wherein one atom of that element is combined with more than four atoms of hydrogen. There is a limit to the number of atoms of hydrogen which a single atom of chlorine can hold in union with itself so as to produce a stable molecular building; and there is a limit to the number of atoms of hydrogen which a single atom of oxygen, or a single atom of nitrogen, or a single atom of carbon, is able to unite with to form a molecular structure that does not fall to pieces.

There is then a limit to the number of hydrogen atoms which can be held by a single atom of any one of the four elements, chlorine, oxygen, nitrogen, and carbon. And what is true of the atoms of these elements is true of the atoms of all the elements. An examination of the numbers of atoms in the molecules of compounds of all the elements that combine with hydrogen, reveals the fact that there is a maximum value for the number of hydrogen atoms wherewith one atom of any particular element can combine to produce a firm molecular structure.

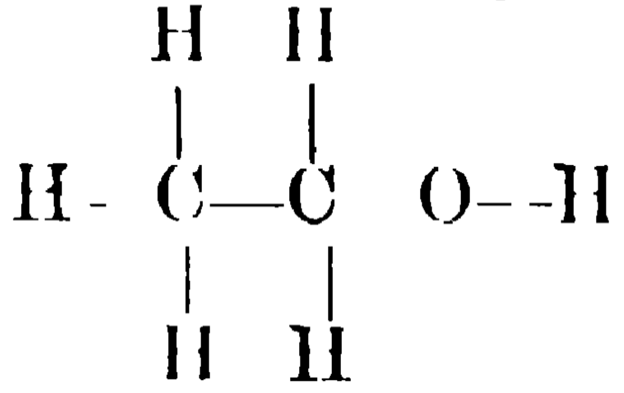
And as with atoms of hydrogen, so with atoms of the other elements. A study of the atomic compositions of molecules, on the lines that have been indicated in the foregoing examples, leads to the notion of a limited atom-holding power as belonging to each kind of elementary atom with respect to any other kind of elementary atom. The results of the study of the atomic compositions of molecules go further than this; they show that there are five elementary atoms which can be used as measurers of the atom-holding power of any other elementary atom. These five atoms are the atoms of hydrogen, of fluorine, of chlorine, of bromine, and of iodine. When we have determined the maximum number of atoms of hydrogen, or the maximum number of atoms of fluorine, or of chlorine, or of bromine, or of iodine, wherewith a single atom of any specified element combines to produce a stable molecule, we have also determined the maximum number of atoms of any kind which that specified atom is able to hold to itself in any molecular building into which it enters.

The moment we grasp the fact that there is a limit to the number of atoms of any kind wherewith a specified atom can enter into direct chemical union to produce a molecular building which does not fall to pieces, we begin to have definite conceptions regarding the structure of molecules. It is now only necessary to determine the limiting value for each kind of atom; I have indicated how this can be done with the help of the atoms of the five elements that serve as measurers of atom-holding power; then to devise a convenient language for expressing the atom-holding powers of the elementary atoms, and their joining together in accordance with the atom-holding power of each; and, finally, to represent the reactions of compounds as connected with the arrangement of the atoms that form the molecules of these compounds,' that arrangement being expressed in the special language which has been devised.

All the elementary atoms belong to one or other of six classes: there are those which can unite directly with but a single other atom; there are those which are able to bind two other atoms to themselves; there are those which can hold three other atoms; there are those which can retain within their sphere of direct action four other atoms; there are those which are able to act directly on, and be directly acted on by, five other atoms; and there are those which can unite into one structure with themselves six other atoms.

I have purposely varied the words whereby I have sought to convey the conception of direct chemical union between atoms. What that union is we do not definitely know; it may be brought about by an attractive force between the atoms, it may be due to the force of gravity conditioned by the forms and the motions of the atoms, but it is more probable that the forces between the atoms are electrical forces. Whatever future research may shew the nature of what we call "direct chemical union between atoms" to be, we are compelled by the facts to think of a molecule as held together by some kind of direct action between atom and atom; we must imagine the molecule as a definite and orderly structure, with each atom arranged in a particular way with respect to the other atoms, although all the atoms are in motion, and with a direct action and reaction between any one atom and a limited number of other atoms. The molecule must be pictured as a sort of miniature solar system.

A simple device is adopted in chemistry for representing the number of atoms between which and any specified atom direct action and reaction can take place in any molecule. The symbol of an element, as we know, is the first letter, or the first and some other letter, of its name; that symbol represents one atom of the element. To the symbol is attached either a Roman numeral, or a number of lines; and the figure, or the number of lines, indicates the atom-holding power of the atom of the element in question. For instance, the symbols C^{IV} and $-\overset{|}{\underset{|}{C}}-$ have the same meaning; and the meaning is that an atom of carbon can hold to itself directly four, and not more than four, other atoms, in a molecule. So the symbols O^{II} and $-O-$ tell that an atom of oxygen is able to unite directly with not more than two other atoms. Then take the symbol for a compound expressed with the help of the device I am endeavouring to explain. Let the compound be water; the symbol $H-O-H$ is meant to set forth the arrangement of the atoms in the molecule of water in so far that the symbol implies direct action, and reaction, between the atom of oxygen and each atom of hydrogen, but the absence of direct union between the two hydrogen atoms. Alcohol is a more complicated compound than water; its composition and molecular weight, and the number of each kind of the atoms that compose the molecule of alcohol, are represented by the symbol C_2H_6O. Now, the reactions of alcohol can be expressed in the special language we are considering, that is, the reactions can be represented as conditioned by the arrangement of the atoms in the molecule of alcohol, by writing the symbol in this way;



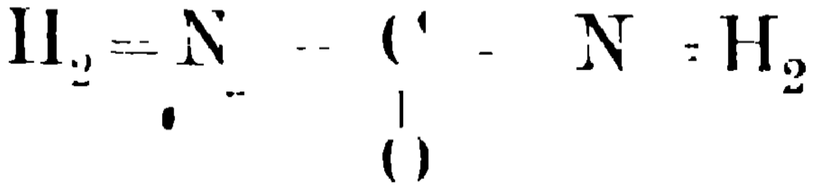
$$\begin{array}{cccc} & H & H & \\ & | & | & \\ H- & C- & C & O-H \\ & | & | & \\ & H & H & \end{array}$$

This symbol is meant to express the fact that if we suppose the atoms of carbon to be in direct union with one another, and if we picture one atom of carbon as directly holding to itself three atoms of hydrogen, and the other atom of carbon as binding to itself two atoms of hydrogen and one atom of oxygen, and if we also think of the atom of oxygen as directly holding the sixth atom of hydrogen; if we keep this arrangement of the atoms C_2H_6O in our mind, then we have a consistent, and, so far as it goes, satisfactory, way of thinking about the reactions of alcohol as conditioned by the number and arrangement of the atoms that form the molecule of that compound. This formula must not be regarded as pretending to be a likeness of the molecule of alcohol; whatever that molecule is like, it is certainly not a collocation of atoms fixed relatively to one another, and all in one plane. This formula, like all formulæ constructed on the same conceptions, is merely a device for aiding accurate thinking about the fundamental question of chemistry, the question, namely, of the connexions between composition and properties. And the device has worked admirably; moreover, it has been found to carry in itself the germs of further developments.

Let us turn back to the special case of connexions between composition and reactions presented by urea and ammonium cyanate. These two compounds have the same molecular weight, and the molecules of the two compounds are composed of the same numbers of the same atoms. The reactions of one of the compounds shew that it is a salt of ammonium, analogous to salammoniac (ammonium chloride) and ammonium carbonate. Now, the only way of representing the compositions of salts of ammonium, agreeably with the reactions of these salts, in the special language of the theory of molecular structure which I have endeavoured to outline in the preceding paragraphs, is to suppose the presence in the molecules of all of them of an atomic group consisting of an atom of nitrogen in direct union with four atoms of hydrogen. The representation of the molecule of ammonium cyanate on this hypothesis is given by the formula

$$H_4 ≣ N - O - C - N$$

The reactions of urea on the other hand are in keeping with an atomic arrangement which is symbolised by the formula



$$\begin{array}{ccccc} H_2=N & - & C & - & N=H_2 \\ & & | & & \\ & & O & & \end{array}$$

Ammonium cyanate reacts as if the molecule of the salt were constructed by joining two groups of atoms, one group being itself made of an atom of nitrogen in direct union with four atoms of hydrogen, and the other group being composed of an atom of carbon directly united with an atom of oxygen and an atom of nitrogen; these groups are indicated in the formula by dotted lines. Moreover, the supposition that these two groups of atoms are held together by direct action and reaction between the oxygen atom and that nitrogen atom which is in connexion with four atoms of hydrogen is more in keeping with the reactions of the salt than any other supposition that can be made concerning the joining of the two atomic groups in the molecule of ammonium cyanate.

If we wish to translate the reactions of urea into the language of the only theory of molecular structure that has been found useful in generalising and suggesting facts, we must represent the molecule of urea as constructed by putting together three groups of atoms; one of these is composed of an atom of carbon directly bound to an atom of oxygen (the group C-O), and the carbon atom of this group is in direct union with two groups, each of which is composed of an atom of nitrogen holding to itself a couple of atoms of hydrogen; the three groups of atoms are indicated in the formula given on p. 176 by dotted lines.

These formulæ, the formula for ammonium cyanate and that for urea, include in themselves the conception of the compound radicle, which was illustrated without the aid of the atomic and molecular theory in Chapter VIII. Now that we have become acquainted with the conceptions of the atom and the molecule, and have gained some slight insight into the ways of representing the connexions between reactions and composition as dependent, among other conditions, on the arrangement of the atoms in the molecules of compounds, we are in a position to think more exactly regarding compound radicles. We now think of a compound radicle as a definite group of atoms, which atoms are arranged in a definite way, and are so firmly held together that the whole group may be moved from one molecule to another without falling to pieces; and we think of many molecules as constructed by putting together various compound radicles.

As we facilitate the comparison, the contrasting, and the classification, of compounds by thinking of the reactions of these compounds as the reactions of extremely small portions of them which we call molecules, so we further facilitate the comparison, the contrasting, and the classification, of compounds by thinking of their reactions as definitely connected with the arrangement in groups of those parts of their molecules which we call atoms; and we yet further facilitate the accurate classification of compounds by the use of a device for representing to ourselves the structure of their molecules, which device has arisen from the use of the atomic and molecular theory, and from the conception of a limit to the number of atoms which can be held directly by any special atom in a molecule, a conception that is itself an outcome of the application to chemical occurrences of the theory of the grained structure of matter.

If the properties of a compound are the properties of the molecule of that compound; if the properties of the molecule are conditioned not only by the nature and number of the atoms that compose it, but also by the arrangement of these atoms; and if it is possible to arrange the same number of the same atoms in various ways consistently with the knowledge we have of the number of atoms which any special atom can hold in direct chemical union; then there ought to be very many instances of the existence of compounds with different properties but the same molecular weights and having molecules composed of the same number of the same atoms. Hundreds, probably thousands, of such cases are known; and almost all the compounds of this kind that have been carefully studied are compounds of carbon, and very many of them are compounds of carbon with some or all of the three elements— hydrogen, oxygen, and nitrogen.

The study of the connexions between composition and chemical properties, especially the compositions and properties of compounds of carbon, is guided, nowadays, by the conception of the molecule as a structure of atomic groups. For instance, the study of the aniline colours, to which I referred in Chapter VII., would be a chaos were it not for this illuminating conception. So that the manufacturer who wishes to make new colours, or to improve the processes whereby well known colours are made, must be thoroughly at home in handling the difficult and intricate questions of molecular structure. We have no other language wherein to express the relations of such bodies as the aniline colours except the language of atoms and molecules, of atomic groups and stable and unstable atomic systems; and to use that language aright demands constant mental alertness, a vivid imagination, and a knack, which comes only from habit, of translating the phrases of the language into the actual reactions of the laboratory, and the reactions observed in the laboratory into the expressions of the language. And this language, like all other living tongues, grows as the wants that have to be expressed by it increase and become more complicated. It is but yesterday that chemists began to try to picture to themselves, in definite ways, the possible arrangements of the atoms of molecules in three dimensions in space, and already many new terms have been introduced to express the new conceptions. And it is so easy to construct a little phrase book for oneself, and to set out hoping to understand and to be understood. But the traveller soon returns liscomfited, lost, perplexed. He thought he had asked correctly, in the laboratory, for a new colour, or a new drug; but nature gave him only a nasty mess. He must begin at the beginning, and he must learn the language in sentences, not in detached words.

Success in many of our staple industries is impossible without a fair knowledge, a knowledge that is accurate so far as it goes, of chemical transformations, and of the means whereby these transformations are expressed, compared, contrasted, and classified. Success in the more refined branches of the chemical trade comes only to the man who is himself an accomplished chemist, or who has the foresight to employ, and to be guided by, a thoroughly trained and thoroughly efficient chemist. And to become an efficient and practically successful chemist means that a man shall have devoted years to the study of problems that deal with the connexions between the structures of molecules and the properties of the compounds which are formed by the coalescence of molecules; it means an apparent wandering far from the path trodden bare by the feet of those who with a gentle irony call themselves "practical men"; but it means treading the only path that leads to those practical results which can be translated into hard cash. I would appeal once more to the history of the German chemical trade in support of this assertion.

Soap-making; the manufacture of paraffin, and the separation and purification of petroleum oils; cheese-making, and most of the operations connected with the feeding of plants and animals on the farm; sugar-making; the preparation of alcoholic drinks; the manufacture of explosives and smokeless powders; tanning; dyeing; calico printing, and the making and applying of colours; preparing paints for use, and devising suitable vehicles for the application of paints, and proper varnishes for locking up the painted surfaces from the effects of weather; the action and application of disinfectants, and antiseptics; the manufacture of anæsthetics; the preparation of new therapeutic agents: to carry on any one of these industries, or arts, successfully, even if by success is meant nothing more than monetary success, requires a knowledge of chemical facts and chemical laws; and not one of these arts or industries can be improved, permanently and fundamentally, otherwise than by the application to the practice of them of that profound chemical knowledge which is gained, and gained only, by the study of problems which seem to the unimaginative man to be absolutely unconnected with the practice of anything that is useful to mankind.

Let us turn back for a short time to the study of the structure of molecules. This study has led to the recognition of molecular symmetry. In the light of recent researches into the connexions between composition and properties, it is necessary to think of the properties of a fairly complex molecule as conditioned by an adjustment of the properties and the positions relatively to one another, of the various compound radicles which form the molecule. Perhaps the substitution of a certain compound radicle for some other atom, or atomic group, in a molecule may carry with it such excessively pronounced properties of one kind or another that the molecule becomes unstable and ready to fall to pieces; then the introduction of another atomic group, with properties very different from those of the group that has made the molecule, as we may say, lopsided, will restore the threatened equilibrium of the structure. As an illustration, look at some of the aniline colours. Let us suppose that the structure of the molecule of a certain compound which dyes a blue-purple is so far known that a definite structural formula has been assigned to the compound; a certain atomic group is introduced in the place of one of the hydrogen atoms in the molecule of this compound, and the result is a compound which dyes an extremely pronounced blue; another compound radicle is introduced in place of an atom of hydrogen in the molecule of the original compound, and the product dyes a red-purple. Now it is wished to produce a compound which will dye a rich purple, neither too blue nor too red; therefore two atomic groups are introduced into the molecule, one of which groups is known to carry with it the property of dyeing blue, and the other the property of dyeing red; the result is that the blueing tendency of one group of atoms is balanced by the reddening tendency of the other group, and a compound is produced which dyes the wished-for purple shade. Molecular symmetry is insured by opposing one group of atoms to another within the molecule.

"Symmetry," says Ruskin, "is the opposition of equal quantities to each other." In molecular architecture symmetry is attained by opposing various groups of atoms which are not necessarily equal quantities, if by that is meant containing equal quantities of matter as measured by weight, but which produce equal changes, although changes in opposite, or at least in different, directions, in the properties of the molecule. Now the effect of this or that atomic group on the properties of a molecule can be determined only by introducing the group in question into many different molecules, and examining the effects produced on the properties of these molecules. It is the old difficulty. You cannot take a group of atoms in your hand and examine and tabulate its properties, and then tell in what ways the properties of any particular molecule will be modified by the substitution of that group for some one or more of the atoms in the molecule; just as a study of the properties of an element taken by itself does not help you to foretell what kind of properties will belong to the compounds of that element. There is only one method: in the latest developments of chemistry, which may be called the study of molecular symmetry, as in the earliest attempts to connect the properties of elements with the properties of their compounds, the only way by which real knowledge is gained is the constant and accurate examination of changes of properties, and changes of composition, and the attempt, constantly made, to connect these two kinds of changes and to express the connexions in some clear and exact, although it may be, and indeed must be, extremely symbolic, language.

There always have been, and there always must be, two lines along which chemistry advances: the science advances by studying composition, and by studying properties; but the study of chemical composition means the looking to changes of composition, and the study of chemical properties is the examination of changes of properties; and all the great advances are made by combining the two lines of research, and by framing generalisations which connect definite changes of one kind with definite changes of the other kind.

But what is the good, what is the use, says some one, of theories about molecules and atoms, things that have only a hypothetical existence, things that if they exist at all are so minute that no mortal eye can ever see them? Let us keep to facts, and then we are on safe ground. Well then, keep to what you call facts; and you will be left behind; you will be left floating on your little crazy raft of crumbling facts, desolate, panting, distressed, when by the help of the swimming belt of theory you might have reached solid land.

The theory of atoms and molecules is a guide to definite and accurate thinking about facts; every day it leads to the discovery of fresh facts —one sometimes wishes there were not quite so many of them; and every day it extends the meaning and the scope of the facts that were thought to be known already. And to be in the habit of thinking about such things as molecular structure, and the connexions between the arrangements of the parts, and the properties of the whole, of these minute portions of matter; to be in the habit of connecting these considerations with operations that proceed on a vast scale in nature, on a smaller but yet very large scale in manufacturing operations, and on a yet smaller scale in the laboratory; to have such conceptions of order, plan, arrangement, and symmetry in one's mind, and to be constantly translating these conceptions into hard solid facts in the laboratory; to be doing those things humanises a man, and serves as a corrective to the brutalising tendencies of life which are so numerous and so violent.

The atoms are the ultimate building stones wherewith chemistry constructs all her varied buildings. And there is no doubt that all the properties of all the compounds, and the compositions of all compounds, are connected with the relative weights of the atoms of the elements in a definite way, and in a way which can be stated in such a form as to admit of direct application. It was a profound truth that was expressed by the great Russian chemist Mendeléeff, when he said that, "chemistry recognises how changes take place in combinations of the unchanging." The unchanging things are the atoms of the elements; the combinations are the molecules both of elements and compounds; and the business of chemistry is to trace the changes of properties which are brought about by combining those unchanging atoms so as to form different kinds of molecules.

CHAPTER X.

SUMMARY AND CONCLUSION.

I HAVE tried in the preceding chapters of this book to indicate the prominent characteristics of those material changes which are the subject matter of the science of chemistry; to illustiate the chemist's classification of material things into elements and not-elements, and his division of the latter class into compounds and mixtures; to sketch the methods, and to state the main results of applying these methods, which lead to the representation of the compositions of compounds in terms of the elements that unite to form, and can be obtained by breaking up, those compounds; to give examples of chemical properties, or reactions, as distinguished from physical properties, and to indicate by the examples given the way in which chemists set about the study of the reactions of elements and compounds, and the general character of the results they obtain. I have also attempted to state and illustrate the essential problem of chemistry, which is to connect properties with composition, and changes of properties with changes of composition; in doing this I have been obliged to deal with the only theory of the structure of matter which has furnished a good working hypothesis for setting forth the observed connexions between composition and reactions; and I have found it necessary to say something about the special language, arising out of that theory, which chemists use as an instrument to aid them in expressing the connexions that they observe between reactions and composition, and also as a means for suggesting relations that may be submitted to the test of experiment.

I have not attempted to follow the historical order of the development of chemical science; but from time to time I have suggested contrasts between older and more modern views of the phenomena with which chemistry concerns itself. I have been obliged, from the condition of my task, to ignore vast portions of the chemical domain; I have, indeed, been able only to sketch in outline a chapter taken here and there, but I hope not altogether in a haphazard way, from the story of chemistry.

Of the chemists themselves, the men who have studied the transformations of matter, and have gradually brought the elucidation of those transformations to the point it has reached today--for the goal is yet far off--nothing, or practically nothing, has been said. These men belonged to various nations; they were of different temperaments, some were slow and plodding, others brilliant, rapid, and versatile; but they were all incited by a regulated curiosity, and were led on by strong, imaginative, commonsense. In this country we had Black, Professor at Edinburgh, the most methodical of men; Priestley, erratic, original, and full of new discoveries; Dalton, essentially a thinker rather than an experimenter; Davy, the most brilliant and the most enthusiastic of English chemists; Cavendish, the careful worker, and the founder of large branches of experimental chemistry; Graham, the atomist, and the forerunner of the physical chemists of to-day; and Faraday, the perfect type of a scientific student of nature. France boasts of Lavoisier, the founder of scientific chemistry, and the greatest name in the history of the science; but the Republic declared there was no need for men of science, and the guillotine fell remorselessly. France produced Dumas also, who lived and worked from the time when organic chemistry began till our own days; an enthusiastic student, a brilliant orator, a great chemist. Of the many great names in the history of chemistry, Germany claims a fair share: Liebig, who alone would add lustre to the annals of any nation; Humboldt, who might almost be said to have taken all knowledge as his province; Wohler, one of the greatest workers in the domain of mineral chemistry; Hofmann, the greatest of organic chemists; and Bunsen, who is still with us, although his working days are finished. Sweden is immortalised in chemistry by the work of Scheele and Berzelius; Italy boasts of Avogadro, and Cannizzaro who still lives and labours; and among chemists none has been more distinguished for philosophic insight and penetrative, accurate imagination than the Russian Mendeléeff, who is still in the thick of the fight. There are many other great names in the history of chemistry; but those I have mentioned suffice to prove that science knows no nationality.

Chemistry extends in two directions; it leads the man who studies it to the highest and most recondite theories, and the most imaginative speculations, concerning the nature of matter; and it has a part in very many of our manufacturing industries, and touches almost every action of our daily lives. It is the most homely, and also the most detached, of the sciences. Chemistry is concerned with the commonest acts of the ordinary lives of men; and in studying chemistry it is literally true that "there is not a moment that passes in which we do not hold the infinite in our hand."

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